Capacity expansion planning of integrated energy system based on multi-energy coupling

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Abstract: This paper proposes a comprehensive energy expansion planning method based on multi-energy coupling, and establishes a mixed integer linear programming model with the goal of minimizing the sum of investment, operation, power shortage, and wind curtailment costs. The model can be used on the basis of ensuring computational efficiency. In the above, the uncertainty of wind power is accurately explored, and a two-stage planning and solving strategy based on the scenario method is established to ensure the efficiency and feasibility of the model solution. GAMS is used to optimize the calculation of the IEEE14-NGS14 example system, and the result of the optimal expansion plan proves the correctness and effectiveness of the method proposed in this paper.

1. Introduction

With the increasingly tense relationship between energy supply and demand, the transformation and upgrading of energy is even more urgent. Integrated energy system refers to a new integrated energy system that uses advanced technology and management models to integrate multiple energy resources such as oil, coal, natural gas and electricity in the region to meet diversified energy demand while effectively improving energy efficiency.

At present, some experts and scholars at home and abroad have carried out relevant research on the planning of integrated energy systems. The existing research on the coupling mechanism of complex multi-energy is mainly focused on the control model of the coupling device and the principle of the coupling technology. Among them, the literature [1-2] proposed a new multi-objective optimization model for integrated energy system design, established electric, heating and cooling systems, obtained the Pareto frontier of multi-objective problems through the NSGA-II method, and four design schemes were selected in the Pareto Frontier and compared to illustrate the reliability of the resulting optimization model. In addition, a two-stage optimization method for coupled capacity planning and operation problems was also proposed; literature [3] The energy station is the core energy coupling link for analysis, focusing on the high-dimensional nonlinear modeling of the electricity-gas-heat system, and analyzing the complementary characteristics and coupling relationships of the electricity-gas-heat energy subsystems. Regarding the expansion planning model of the integrated energy system, literature [4] considered the value chain of natural gas and studied the long-term, multi-region, multi-stage expansion planning of the gas-electric coupling system. Literature [5] proposed a linear expansion planning model for gas-electric coupled systems containing gas generators with the goal of minimizing the total investment and operating cost. However, the above research did not combine wind power with...
expansion planning. It is necessary to further rationally and effectively consider the uncertainty of wind power in the expansion planning of IES, in order to improve the rationality and economy of IES planning.

2. IES extended optimization planning model

The objective function of the IES extended optimization planning model with wind power is to minimize the expected value of the net present value of the total planning cost of the coupled system under different wind power output scenarios, including investment costs, operating costs, power shortage costs, and wind abandonment costs. Its goal is expressed as:

$$\min Z = \sum_{s=1}^{s_N} \pi^s \sum_{t=1}^{T} \lambda_t ((1 - \gamma \frac{\lambda_t}{\lambda_a}) C_{\text{inv}}^s (t) + C_{\text{op}}^s (t) + C_{\text{seems}}^s (t) + C_{\text{w}}^s (t))$$

among them:

$$C_{\text{inv}}^s (t) = \sum_{i=1}^{i_N} u_i P_i^{\text{max}} (x_i^t - x_i^{t-1}) + \sum_{l=1}^{l_N} L_i P_i^{\text{max}} (x_i^t - x_i^{t-1}) + \sum_{f=1}^{f_N} F_f P_f^{\text{max}} (x_f^t - x_f^{t-1}) + \sum_{c=1}^{c_N} C_f P_c^{\text{max}} (x_c^t - x_c^{t-1}) + \sum_{p=1}^{p_N} P_p P_p^{\text{max}} (x_p^t - x_p^{t-1})$$

$$C_{\text{op}}^s (t) = \sum_{i=1}^{i_N} \sum_{d=1}^{d} \sum_{h=1}^{h} (\sum_{u}^u) P_{i,d,h} O_{i,d} + \sum_{f=1}^{f_N} \sum_{d=1}^{d} \sum_{h=1}^{h} (\sum_{o}^o) P_{f,d,h} O_{f,d} + \sum_{c=1}^{c_N} \sum_{d=1}^{d} \sum_{h=1}^{h} (\sum_{c}^c) P_{c,d,h} O_{c,d}$$

$$C_{\text{seems}}^s (t) = V \sum_{b}^b \Delta L_b$$

$$C_{\text{w}}^s (t) = C_w \sum_{b}^b \Delta C_b$$

$$\lambda_t = 1/(1 + \gamma)^{t-1}$$

$$Z$$ is the total planning cost; $$s$$ represents the $$s$$-th wind power scenario, There are $$s_N$$ total of wind power output scenarios, $$\pi^s$$ indicates the probability of occurrence of the $$s$$-th wind power scene; $$T$$ is the planning cycle, that is, the total planning years; $$d$$ represents the number of typical days in a year; $$h$$ represents the number of periods in a day; $$i_N$$, $$f_N$$, $$c_N$$ and $$p_N$$ respectively indicate the number of conventional units, gas boilers, CHP units, PTG devices and natural gas sources; $$C_{\text{inv}}^{s, (t)}$$ is the total investment cost of the system in year $$t$$ under the $$s$$th scenario; $$C_{\text{op}}^{s, (t)}$$ represents the unit capacity investment cost of conventional units, transmission lines, gas boilers, CHP and PTG; $$C_{\text{seems}}^{s, (t)}$$, $$C_{\text{w}}^{s, (t)}$$, $$C_{\text{w}}^{s, (t)}$$ respectively indicate the capacity of the above-mentioned equipment; $$C_{\text{op}}^{s, (t)}$$ is the total operating cost of the system in year $$t$$ in the $$s$$ scenario; $$C_w$$, $$C_{\text{w}}$$, $$C_{\text{w}}$$ and $$C_{\text{w}}$$ respectively represent the unit operating costs of conventional units, gas boilers, CHP and PTG and natural gas sources; $$C_{\text{seems}}^{s, (t)}$$, $$C_{\text{seems}}^{s, (t)}$$, $$C_{\text{seems}}^{s, (t)}$$ and $$C_{\text{seems}}^{s, (t)}$$ respectively represent the output value (power of electricity and gas) of the above equipment in the $$s$$ scenario per year and hour of a typical day; $$C_{\text{seems}}^{s, (t)}$$ is the total power shortage cost of the system in year $$t$$ in the $$s$$ scenario; $$V$$ is the unit power shortage cost; $$\Delta L_b$$ is the insufficient amount of electric energy; $$C_{\text{w}}^{s, (t)}$$ is the total wind curtailment cost of the system in year $$t$$ under the $$s$$ scenario; $$C_{\text{w}}$$ is the unit wind curtailment cost; $$\tau$$ is the amount of air curtailment; $$\rho$$ is the discount rate of funds; $$\gamma$$ is the present value coefficient of year $$t$$.

3. Multi-energy coupling constraints

The constraints of the coupled system include: operational status constraints, energy center constraints, power system constraints, natural gas system constraints, and reliability constraints.

3.1. Constraints on operational status

After the candidate conventional units$$^t$$, transmission lines$$^t$$, gas boilers$$^t$$, CHP units$$^t$$, and PTG equipment$$^t$$ are put into operation in year $$t$$, their state variables will change from 0 to 1, and their
operational status will not be changed in subsequent planning years, and the current planning year is less than each. The equipment will not be put into operation when the equipment is put into operation for the minimum year. Can be expressed as:

\[ x_{a,i}^t \leq x_{d,j}^t, \quad \forall a \in i^*, l^*, f^*, c^+, p^+, \forall t \]  \hspace{1cm} (7)

\[ x_{a,j}^t = 0, \quad \forall a \in i^*, l^*, f^*, c^+, p^+, \forall t < T^* \]  \hspace{1cm} (8)

\( i^* \) indicates the operational status of different equipment, and the state variable of the existing equipment is set to 1; \( T^* \) is the minimum commissioning year of each equipment (the minimum year that can be put into operation).

3.2. Energy center constraints

The energy conversion relationship of each energy conversion equipment in the energy center can be expressed by equations (9)-(12). The upper and lower limits of heat and electricity production of each put into operation and candidate equipment are represented by equations (13)-(15).

\[ P_{c,h,t}^c = \eta_{CHP} G_{c,h,t} \]  \hspace{1cm} (9)

\[ H_{c,h,t}^c = \eta_{heat} G_{c,h,t} \]  \hspace{1cm} (10)

\[ H_{c,h,t}^{heat} = \eta_{heat} G_{c,h,t} \]  \hspace{1cm} (11)

\[ G_{p,d,h,t}^p = \eta_{PTG} P_{d,h,t} \]  \hspace{1cm} (12)

\[ P_{min} x_{c,f} \leq P_{p,d,h,t}^{max} x_{c,j} \quad \forall c \in c^+ \]  \hspace{1cm} (13)

\[ H_{min} x_{f} \leq H_{f,\Delta h,\Delta t}^{max} x_{f,j} \quad \forall f \in \{ F, f^* \} \]  \hspace{1cm} (14)

\[ P_{p}^{min} x_{p} \leq P_{p,d,h,t}^{max} x_{p,j} \quad \forall p \in p^* \]  \hspace{1cm} (15)

\( \eta_{CHP}, \eta_{heat}, \eta_{PTG} \) respectively represents the electrical efficiency, thermal efficiency of CHP, and the thermal efficiency of gas boilers; \( c^+ \) represents the gas consumption power of CHP and PTG respectively; \( c^p \) and \( c^p \) respectively represents the gas production power and power consumption of the PTG device; \( \eta_{CHP}, \eta_{heat}, \eta_{PTG} \) respectively represents the electrical efficiency, thermal efficiency of CHP, the thermal efficiency of gas boilers and the efficiency of PTG; \( F \) represents the collection of existing gas boilers.

3.3. Power system constraints

Power network constraints include: power supply and demand balance constraints (16)-(19), power network flow constraints (20) (21), and reserve capacity constraints (22).

\[ \sum_{i=0}^{n} P_{i,d,h,t}^c + \sum_{r=0}^{m} P_{i,d,h,t}^r - \sum_{k=0}^{l} P_{i,d,h,t}^l = P_{d,h,t}^d \]  \hspace{1cm} (16)

\[ \Delta L^c = \sum_{i=0}^{n} \sum_{r=0}^{m} \sum_{k=0}^{l} P_{i,d,h,t}^c - \sum_{r=0}^{m} P_{r,d,h,t}^c + \sum_{k=0}^{l} P_{k,d,h,t}^c - \sum_{r=0}^{m} P_{r,d,h,t}^c + \sum_{k=0}^{l} P_{k,d,h,t}^c \geq 0 \]  \hspace{1cm} (17)

\[ \Delta C^c = \sum_{i=0}^{n} \sum_{r=0}^{m} \sum_{k=0}^{l} P_{i,d,h,t}^c - \sum_{r=0}^{m} P_{r,d,h,t}^c + \sum_{k=0}^{l} P_{k,d,h,t}^c - \sum_{r=0}^{m} P_{r,d,h,t}^c + \sum_{k=0}^{l} P_{k,d,h,t}^c < 0 \]  \hspace{1cm} (18)

\[ P_{i,d,h,t}^c - B_i (\theta_{i,d,h,t} - \phi_{i,d,h,t}) \leq M (1 - x_{i,j}^t), \forall i \in \{ U, i^* \} \]  \hspace{1cm} (19)

\[ P_{i,d,h,t}^c \leq P_{i,d,h,t}^{max} x_{i,j}^t, \forall i \in \{ L, i^* \} \]  \hspace{1cm} (20)

\[ | P_{i,d,h,t}^c - B_i (\theta_{i,d,h,t} - \phi_{i,d,h,t}) | \leq M (1 - x_{i,j}^t), \forall i \in \{ L, i^* \} \]  \hspace{1cm} (21)

\[ \sum_{i=0}^{n} P_{i,d,h,t}^{max} x_{i,j}^t + \sum_{c=0}^{C} P_{p,d,h,t}^{max} x_{p,j}^t + \sum_{c=0}^{C} P_{p,d,h,t}^{max} x_{p,j}^t + \sum_{u=0}^{N} P_{u,d,h,t}^{max} x_{u,j}^t \geq L_{max} (t) + S_k \]  \hspace{1cm} (22)

\( U \) and \( L \) respectively represent the collection of existing conventional units and transmission lines; \( e_{b,\Delta l} \) is the electric power input to the b-th energy center; \( e_{b,\Delta l} \) is the output value of the fan; \( e_{b,\Delta l} \) is the line transmission power; \( B_i \) is the line admittance; \( \theta \) is the phase angle of the nodes at both ends of the line;
\( r(t) \), \( s(t) \) is the end node and start node of the line respectively; \( \Delta e_{r,s} \) is the electric energy imbalance. If the electric energy imbalance is a positive value, it means that the node has insufficient power; if it is a negative value, it means that the node has abandoning wind; \( M \) is a very large number; \( r_{\text{max}}, r_{\text{min}} \) respectively represent the upper and lower limits of conventional unit output; \( p_{\text{max}}, p_{\text{min}} \) respectively indicate the upper limit of line transmission power, CHP unit and wind power output; \( c_{t} \) is the upper limit of electric load in year \( t \); \( s \) is the reserve capacity, which is usually proportional to the electrical load.

### 3.4 Natural gas system constraints

Equation (23) is the natural gas supply and demand balance constraint, which means that the sum of the natural gas source of a certain energy center and the net flow of natural gas entering the node is the total amount of natural gas input to the energy center. Equations (24) and (25) are the upper and lower limits of natural gas source and natural gas flow.

\[
\sum_{r_{pp}rsb} G_{pp,rs,t}^{s} - \sum_{k_{pp}rsb} G_{pp,ks,t}^{s} + \sum_{g_{rsb}} S_{g,rs,t}^{s} = G_{h,rs,t}^{s} \\
G_{gs}^{\text{min}} \leq G_{gs,rs,t}^{s} \leq G_{gs}^{\text{max}} \\
G_{pp}^{\text{min}} \leq G_{pp,rs,t}^{s} \leq G_{pp}^{\text{max}}
\]

\( G_{gs,rs,t}^{s} \) is the natural gas power input to the \( b \)-th energy center; \( G_{gs,rs,t}^{s} \) represents the natural gas flow per hour per typical day per year in the \( pp \) natural gas pipeline in the \( s \) scenario; \( r_{(pp)}, k_{(pp)} \) a represents the end node and start node of the natural gas pipeline respectively; \( c_{(pp)}, c_{(pp)} \) respectively represent the upper and lower limits of gas production from natural gas sources; \( c_{(pp)}, c_{(pp)} \) represents the upper and lower limits of natural gas flow respectively.

### 3.5 Reliability constraints

The insufficient amount of electric energy needs to meet the upper limit constraint:

\[
\Delta L_{n}^{t} \leq L_{n}^{\text{min}}
\]

\( L_{n}^{\text{min}} \) is the upper limit of insufficient electric energy.

### 4. Example analysis

In this paper, the IEEE 14-node power system and NGS14-node natural gas system are used as prototypes to construct an IEEE 14-NGS14 electric-gas-thermal coupling system, as shown in Figure 1. The existing power system includes 5 conventional units, 20 transmission lines and 4 wind farms. The natural gas system includes 2 natural gas sources, 7 gas boilers and 13 natural gas pipelines. The above equipment is located at different nodes of the system. The air, gas, and heat systems operate independently. In addition, there are 11 electrical loads, 7 heat loads and 3 gas loads distributed in different areas in the system. During the planning period, the candidate equipment is 6 conventional units, 10 transmission lines, 4 CHP units, 6 gas boilers and 4 PTG devices. You can choose whether to put into operation and the corresponding time point of operation.
Coupling planning means adding energy coupling devices in the system, such as CHP and PTG. Using the above solution strategy, the final optimal planning result is the commissioning combination 1, and the total planning cost is $13.233 \times 10^9$ USD. The specific planning results and costs are shown in Table 1 and Table 2.

Table 1. Planning results for decoupling and coupling scenarios

| Category          | Case1                  | Case2                  |
|-------------------|------------------------|------------------------|
| Conventional unit | G7, 2; G11, 1          | G7, 2; G11, 1          |
| Transmission line | L2, 5; L23, 9; L28, 4  | L20, 5                 |
| Gas boiler        | F9, 6; F9, 10; F12, 5  | F9, 6                  |
| CHP               | F10                    | C1, 2; C2, 3           |
| PTG               | No                     | P2, 1; P3, 1           |

Note: G stands for conventional unit, L stands for line, F stands for gas boiler, C stands for CHP unit, P stands for PTG unit, and the number after the comma means it is put into operation in the first year.

Table 2. Cost comparison between decoupling and coupling cases

| Cost /10^9 yuan   | Case1 | Case2 |
|-------------------|-------|-------|
| Conventional unit | 0.689 | 0.600 |
| Transmission line | 0.030 | 0.014 |
| Gas boiler        | 0.550 | 0.123 |
| CHP               | No    | 0.345 |
| PTG               | No    | 0.047 |
| Operating costs   | 11.950| 12.312|
| Wind curtailment cost | 0.625 | 0.040 |
| Insufficient power cost | 0.650 | 0.644 |
| Total cost        | 14.641| 15.000|

It can be seen from Table 2 that the overall economy of Case2 is significantly better than Case1. The reason is that the access of the aforementioned coupling elements greatly reduces the operating cost and overall planning cost of the system, and improves the economy of the system. According to specific
analysis, CHP can generate electricity and heat at the same time, which can significantly improve operating efficiency and reduce operating costs in an integrated energy system; while PTG can convert excess wind power into usable natural gas energy, as can be seen from the data in Table 2. The wind abandonment situation of Cases 2 has been significantly improved. Therefore, the coupling planning of electricity-gas-heat will become an important choice for the future energy supply form due to its significant economic and social benefits.

5. Conclusion
This paper takes into account the uncertainty of wind power and studies the IES extended planning method. Based on the energy center model, an IES mixed integer linear programming model with the goal of minimizing the sum of investment, operation, power shortage and wind curtailment cost is established; a two-stage planning and solving strategy based on the scenario method solves the problem that the built model is difficult to directly and efficiently solve the expected value of integer variables; finally, the results of the calculation example verify the effectiveness of the proposed planning method, the effectiveness of the solution strategy and the IES planning; the need to consider the impact of fluctuating wind power.

Acknowledgment
The authors would like to thank the support of the project “the State Grid Corporation Science and Technology Project (SGSDDK00PDJS2000383)”.

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