A Novel Optimization Model of Integrated Energy System Considering Thermal Inertia and Gas Inertia

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Aiming at the energy multivariate heterogeneity of thermal system and natural gas system, a novel optimization model of integrated energy system considering thermal inertia and gas inertia is proposed. First, the dynamic characteristics of the thermal system in the integrated energy system are studied, and the inertia model of the heat network pipeline and thermal building is established. Second, the characteristics of natural gas pipeline network storage are studied, and the natural gas storage and pressure energy generation models are established. Then, the optimization objective of the minimum integrated operating cost of the integrated energy system is established, and the YALMIP solver is used to solve it. Finally, a numerical example is introduced to analyze the operating cost of the integrated energy system in different scenarios, and it is verified that the integrated energy system optimization model considering the inertia of the thermal and gas proposed in this paper can effectively improve the system regulation capability and reduce the system operating cost.

1. Introduction

In order to help the governance of global climate issues, reduce the burning of fossil fuels, and increase the proportion of renewable energy, an integrated energy system is composed of electricity, heat, gas, and other heterogeneous sources with the power system as the center and multenergy flow coupling and complementing have been formed [1–3]. However, with the high proportion of renewable energy and large-scale power electronic devices connected to the power system, the physical inertia is greatly reduced, and the antidisturbance ability is greatly weakened [4–6]. Compared with the traditional power system, the dynamic inertia in the integrated energy system coupled with multiple energy sources of electricity, heat, and gas presents a severe test for the coordinated optimization of the system at multiple time scales [7–10]. Therefore, it is of great significance to analyze the thermal and gas inertia resources of the integrated energy system and to study the thermal and gas inertia and optimization methods of the integrated energy system for realizing the economic and stable operation of the integrated energy system.

There have been some studies on the dynamic characteristics of integrated energy systems. Reference [11] considers the time-delay characteristics of thermal network transmission and establishes an inertial model of thermal system. Reference [12] studied the thermal inertia of electric boiler equipment; established a thermal dynamic model of heat storage, heat transfer, and heat loss; and analyzed the influence of thermal inertia in the operation of the cogeneration system. Reference [13] studied the multiple thermal inertias of thermal systems and proposed an equal energy storage model for the thermal network. Reference [14] took thermal inertial energy into the demand-side response and participated in the optimal scheduling of the integrated energy system. References [15, 16] established a transient model of natural gas pipeline network and used the natural gas pipeline storage model as a constraint to participate in the optimal scheduling of the system. References [17, 18] studied the buffer characteristics of the gas pipeline to smooth load fluctuations to improve system flexibility.

The above research mainly improves the system regulation ability from the thermal inertia of the thermal system or the pipe storage function of the gas pipeline, but does not...
comprehensively consider the thermal and gas inertia. The paper considers the inertia of thermal system and natural gas system to participate in system energy regulation, and proposes an integrated energy system optimization model considering thermal and gas inertia. First, the thermal system inertia model and thermal building inertia model are established, respectively, to study the energy storage characteristics of thermal inertia of thermal system. Second, the inertia model and pressure model of the natural gas pipeline network are established, respectively, to study the energy storage characteristics of the gas inertia of the natural gas pipeline network. Then, under the premise of ensuring the operating reliability of the system, the energy purchase cost is considered comprehensively, and the optimization goal is to minimize the operating cost of the system. Finally, an integrated energy system simulation model verifies the model proposed in this paper. It is verified that the integrated energy system optimization model considering heat and gas inertia proposed in this paper can effectively reduce the system operating cost and improve the system regulation ability.

2. Energy Coupling Model of Integrated Energy System

The system consists of renewable energy power generation equipment, gas boilers, gas turbines, electric boilers, combined heat and power (CHP), power to gas (P2G), and multiple loads [19]. In this paper, the thermal inertia of the thermal network, electric boilers, thermal buildings, and the pipe storage characteristics of the natural gas pipeline are modeled, and the support of the dynamic inertia of the thermal network and the gas network on the system regulation ability is analyzed. The structure of the integrated energy system is shown in Figure 1.

The power distribution system, heat pipe network, and gas transmission network of the integrated energy system have different time scales. Therefore, different from the traditional power system, the integrated energy system does not have real-time energy balance due to its heat network and gas network. The pipeline storage surplus of the heat network and the gas network has the characteristics of stored energy in a broad sense.

3. Dynamic Inertia Analysis of Thermal System

Inertia in a narrow sense is used to describe the magnitude of an object’s inertia. Inertia refers to the dynamic characteristics of stored energy in a broad sense.

3.1. Thermal Inertia Model of Heat Pipe Network. For the production and transmission of heat energy, the main energy transmission medium of the heat pipe network is hot water, the flow rate of the hot water is slow during the transmission process, and there is a certain amount of heat energy between the water inlet and the water outlet. At the same time, the ambient temperature of the pipe network also has a great influence on the hot water temperature [20]. Therefore, it is necessary to model and analyze the transmission delay and temperature loss of hot water. The hot water transmission delay at the end of the heat pipe network can be expressed as follows:

$$\tau_h = \frac{\pi \rho L d^2}{4q},$$

(2)

where \(\rho_h\) is the density of the transmission medium; \(L\) is the length of the pipe; \(d\) is the diameter of the pipe; and \(q\) is the flow rate of the pipe.

The delay of hot water delivery results in slow dynamic characteristics of the heat network, that is, the temperature at the beginning and end of the pipe is different. Considering

\[
\begin{bmatrix}
L_E (\tau_E + t) \\
L_G (\tau_G + t) \\
L_H (\tau_H + t)
\end{bmatrix}
= 
\begin{bmatrix}
\lambda_1 \eta_{\text{CHP,E}} & \delta_1 & 0 \\
\lambda_2 & \delta_2 \eta_{\text{P2G}} & 0 \\
\lambda_3 \eta_{\text{CHP,H}} & \delta_3 \eta_{\text{EB}} & 1
\end{bmatrix}
\begin{bmatrix}
P_{E,\text{pur}} (t) \\
P_{G,\text{pur}} (t) \\
P_{H,\text{pur}} (t)
\end{bmatrix},
\]

(1)
the effect of the residual energy in the thermal network on the system regulation, the thermal inertia can be expressed as follows:

\[ Q_{in}(t) = L_H(t) - \left[ Q_{EB}(t) + Q_{CHP}(t) + Q_{SH}(t) \right], \]  

where \( Q_{in}(t) \) is the energy storage regulation power of the heat network in the \( t \) period; \( L_H(t) \) is the heat load in the \( t \) period; \( Q_{EB}(t) \), \( Q_{CHP}(t) \), and \( Q_{SH}(t) \) are the thermal power of the electric boiler, the cogeneration unit, and the heat storage device in the \( t \) period, respectively.

3.2. Building Thermal Inertia Model. In terms of heat load, the thermal inertia of a building reflects the ability of the building’s thermal insulation structure to maintain temperature loss in different environments. The thermal inertia of a building is related to the area of the thermal insulation structure to maintain temperature loss in different environments. Therefore, the dynamic model of a building can be expressed as follows:

\[
\begin{align*}
H_{it}^{KT} &= \kappa S_i \left( T_{in,i}^t - T_{in,i}^{out} \right) \left( 1 + \lambda_i^h \right) \left( 1 + \lambda_i^l \right), \\
H_{it}^{CO} &= 0.288 \lambda_{in} V_i C_P \rho_i \left( T_{in,i}^t - T_{in,i}^{out} \right),
\end{align*}
\]

where \( \kappa \) is the heat transfer coefficient of the building at node \( i \); \( H_{it}^{KT} \) is the heat load of the building insulation structure at node \( i \) of the heat network in the \( t \) period; \( S_i \) is the area of the building insulation structure at the node \( i \); \( T_{in,i}^t \) is the interior temperature of the building at the node \( i \) at the \( t \) period; \( T_{in,i}^{out} \) is the outdoor ambient temperature of the building at node \( i \) in the \( t \) period; \( \lambda_i^h \) and \( \lambda_i^l \) are the correction coefficient of the building height and the direction of the building at the node \( i \), respectively; \( H_{it}^{KT} \) is the cold air infiltration heat load of the heating area at the node \( i \) in the \( t \) period; \( \lambda_{in} \) is the minute number of air changes in each stage; \( V_i \) is the volume of the building’s thermal insulation structure at node \( i \); \( C_P \) is the specific heat capacity of the air at constant pressure; and \( \rho_i^{out} \) is the outdoor air density in the \( t \) period.

The thermal inertia of a building in a dynamic environment can be expressed as follows:

\[ t_{in,i}^{out} = t_{in,i}^{in} + \frac{\left( H_{load,i}^{out} - H_{in,i}^{KT} - H_{in,i}^{CO} - H_{in,i}^{in} \right) \Delta t}{C_{Hi} M_i}.
\]

where \( C_{Hi} \) is the specific heat capacity of indoor air and \( M_i \) is the air quality of the heating environment at node \( i \).

4. Dynamic Inertia Analysis of Gas Pipeline Network

Based on the storage and pressure characteristics of natural gas pipelines, a gas inertia output model is established.

4.1. Dynamic Model of Gas Pipeline Network. The gas pipeline transmission model is as follows:

\[
\begin{align*}
\frac{\partial P}{\partial x} + \frac{\partial P}{\partial t} &= 0, \\
\frac{\partial P v}{\partial x} + \frac{\partial P v^2}{\partial d} + \frac{\partial P v^2}{\partial d} + 9.8 \rho \sin \phi &= 0,
\end{align*}
\]

where \( \rho \), \( v \), and \( P \) are the density, flow rate, and pressure of natural gas, respectively; \( x \) and \( t \) are spatial and temporal variables, respectively; \( \delta \), \( d \), and \( \phi \) are the friction coefficient, diameter, and relative inclination of the pipeline, respectively.

Pipeline pressure and flow meet

\[
\begin{align*}
P &= M_S T_G \rho, \\
f &= \rho v S,
\end{align*}
\]

where \( M_S \) is the quotient of the gas constant and the molar mass; \( T_G \) is the natural gas temperature; and \( S \) is the cross-sectional area of the pipeline.

The natural gas flow rate has little effect on the change of pipeline pressure, so the effect of natural gas flow rate is ignored. It is assumed that the pipeline is in an ideal state, the relative inclination angle is zero, the cross-sectional area of the pipeline is constant, and the inflow and outflow natural gas is constant temperature. Therefore, the dynamic model of natural gas pipeline can be simplified as follows:

\[
\begin{align*}
\frac{\partial P}{\partial t} + M_S T_G \frac{\partial f}{\partial x} &= 0, \\
\frac{1}{S} \frac{\partial f}{\partial x} + \frac{\partial P}{\partial x} + \frac{\partial P}{\partial d} f &= 0.
\end{align*}
\]

4.2. Natural Gas Pipeline Network Pressure Model. In order to study the corresponding state of the pressure at the end of the natural gas pipeline network, according to the finite element approximation idea, the natural gas dynamic model can be simplified as follows:

\[
\begin{align*}
\frac{\partial f}{\partial x} &= \frac{f_{out,t} - f_{in,t}}{l}, \\
\frac{\partial P}{\partial x} &= P_{out,t} - P_{in,t},
\end{align*}
\]

where \( l \) is the length of the natural gas pipeline network; \( f_{in,t} \) and \( f_{out,t} \) represent the inlet flow and outlet flow of the natural gas pipeline network at time \( t \) respectively; \( P_{in,t} \) and \( P_{out,t} \) represent the inlet pressure and outlet pressure of the natural gas pipeline network at time \( t \), respectively.

Assuming that the pressure of the natural gas pipeline network is constant under ideal conditions, then

\[
\begin{align*}
\dot{P}_{out,t} + \frac{M_S T_G}{S l} \left( f_{out,t} - f_{in,t} \right) &= 0, \\
\dot{f}_{in,t} + \frac{S}{l} \left( P_{out,t} - P_{in,t} \right) + \frac{\partial v}{\partial d} f_{in,t} &= 0.
\end{align*}
\]
4.3. Gas Inertial Energy Storage Characteristic Model. Considering the effect of gas inertia on the improvement of system regulation capability and the operation constraints, a gas-inertia energy storage characteristic model is established.

When there is a power shortage in the system, the pressure at the end of the natural gas pipeline network will decrease according to a negative exponential curve.

Therefore, the pressure at the end of the gas pipeline network is a linear superposition of the step response and the impulse response. Then use the pull transformation to solve the problem, and it is obtained that the pressure at the end of the gas pipeline network will decrease according to a negative exponential curve.

\[ P_{out,t} = P_{out}\min - \frac{1}{\tau_G} \left( \frac{t}{\tau_G} \right)^n \]

The adjustment time of gas inertia energy storage characteristics is as follows:

\[ T_G = t'' - t_1. \]

Assuming that the natural gas pipeline network completes the inertial energy release behavior at time \( t'' \), then \( t'' \) needs to satisfy

\[ t'' \leq t''_{\max}. \]

The gas inertia adjustment recovery time interval is as follows:

\[ t_\min = t''_{\max} - t''. \]

At time \( t'' \), the natural gas pipeline network needs to continue to provide power support for the system. At the same time, the instantaneous value of \( f_{out} \) jumps to \( f_3 \), then

\[ t'' \leq t''_{\min}. \]

The energy storage characteristics of gas inertia can be expressed as follows:

\[ f_{out,t}'' = \zeta(t'' - f_1) + f, \]

where \( f_1 \) is the initial value of \( f_{out} \); \( f_2 \) is the peak value of \( f_{out} \); \( \zeta \) is the step function; and \( \zeta \) is the impulse function.

5. Coordinated Optimization Model of Integrated Energy System Considering Thermal and Gas Inertia

Considering the thermal inertia and gas inertia in the integrated energy system to improve the system regulation ability, an integrated energy system optimization model considering thermal and gas inertia is established.

5.1. Objective Function. The integrated energy system coordination optimization model considering heat and gas inertia is to make full use of the dynamic characteristics of the heat network and the gas network, and reasonably adjust the output of energy production equipment, energy conversion equipment, and energy storage devices. Under the premise of ensuring the reliability of the system, the optimization goal is to minimize the operating cost of the system. The objective function can be expressed as follows:

\[ \min C(t) = \sum_{t=1}^{24} \left( C_{op}(t) + C_E(t) + C_G(t) + C_H(t) \right). \]

where \( C(t) \) is the total operation cost of the coordinated optimization of the integrated energy system in the \( t \) period; \( C_{op}(t) \) is the operation and maintenance cost of the system equipment in the \( t \) period; \( C_E(t) \) is the electricity purchase cost in the \( t \) period; \( C_G(t) \) is the gas purchase cost in the \( t \) period; \( C_H(t) \) is the heat purchase cost in the \( t \) period; \( C_{op}(t) \) is the unit capacity cost of the equipment; \( N_y \) is the total number of energy supply units in the system, where \( y \in \{ CHP, EB, P2G, GT, GS, HS, EE \}; \omega \) is the proportion of the operation and maintenance cost to the initial investment cost; \( \lambda \) is the annual interest rate; \( n \) is the effective service life of the energy storage device; \( C_y(t) \) is the unit capacity cost of the equipment; \( P_E \) and \( P_G \) are the purchase price of electricity and gas, respectively; \( P_E(t) \) and \( P_G(t) \) are the interactive power between the integrated energy system and the power grid and the gas network in the \( t \) period, respectively; and \( h \) and \( g \) are the thermal inertia time of the actual heating pipeline and the inertia time of the gas supply pipeline, respectively.
5.2. Restrictions

(1) Power balance constraint is as follows:
\[ P_{PV}^{i,t} + P_{WP}^{i,t} + P_{GT}^{i,t} + P_{CHP}^{i,t} + P_{in}^{i,t} - \sum_j P_{ij,t}^l = P_{ij,t}^l + P_{ij,t}^{P2G} + P_{ij,t}^{HS}, \]
where \( P_{WP}^{i,t} \) and \( P_{PV}^{i,t} \) are the wind power output and photovoltaic output of node \( i \) in period \( t \), respectively; \( P_{GT}^{i,t} \) is the gas turbine output of node \( i \) in period \( t \); \( P_{CHP}^{i,t} \) is the output of CHP unit at node \( i \) in period \( t \); \( P_{in}^{i,t} \) is the electricity purchased by node \( i \) in period \( t \); \( P_{ij,t}^l \) is the electrical load of node \( i \) in the \( t \) period; \( P_{ij,t}^{P2G} \) is the gas production power of the node \( i \) in the \( t \) period; and \( P_{ij,t}^{HS} \) is the heat storage power of the node \( i \) in the \( t \) period.

(2) Thermal inertia constraint is as follows:
\[ H_{HS}^t = f\left( T_{HS}^t, P_{HS}^t \right), \]
\[ T_{out}^t = g\left( T_{in}^t, H_{load}^t, H_{loss}^t \right), \]
where \( f \) is the output function of thermal inertia; \( g \) is the temperature function of the pipeline considering the thermal inertia of the load side of the heat network; \( h \) is the temperature function of the building considering the thermal inertia of the load side of the heat network; and \( H_{HS}^t \) is the heat loss composed of three parts: the heat load of the building envelope, the heat load of cold air penetration, and the heat load of ventilation.

(3) Air inertia restraint is as follows:
\[ M_{s-1,s,t} = \varphi\left( M_{s-1,s-1,t}, Q_{s,t}, Q_{s-1,t} \right), \]
\[ Q_{s-1,s,t} = \psi\left( P_{s,t}, P_{s-1,t} \right), \]
where \( \varphi \) is the storage function of the gas pipeline network and \( \psi \) is the flow function of the pipeline.

(4) The working pressure range of the gas pipeline network is as follows:
\[ P_{out.t.min} \leq P_{out,t} \leq P_{out.t.max}, \]
where \( P_{out.t.max} \) and \( P_{out.t.min} \) are the upper limit and lower limit of the pressure at the end of the gas pipeline network, respectively.

(5) CHP unit output constraint is as follows:
\[ \begin{align*}
H_{CHP}^t &= P_{CHP}^t k_r, \\
Q_{CHP}^t &= \frac{P_{CHP}^t}{\eta_{CHP}}
\end{align*} \]
where \( H_{CHP}^t \), \( P_{CHP}^t \), and \( Q_{CHP}^t \) are the heating power, power supply, and gas consumption of the cogeneration unit in the \( t \) period, respectively; \( k_r \) and \( \eta_{CHP} \) are the energy supply parameters of the cogeneration unit; \( k \) is the calorific value of gas.

(6) GT unit output constraint is as follows:
\[ Q_{GT}^t = \frac{P_{GT}^t}{\eta_{GT}}, \]
where \( Q_{GT}^t \) and \( P_{GT}^t \) are the gas consumption and electricity consumption of the gas turbine in the \( t \) period, respectively; \( \eta_{GT} \) is the power supply efficiency of the gas turbine.

(6) P2G unit output constraint is as follows:
\[ Q_{t}^{P2G} = \frac{P_{t}^{P2G} \eta_{P2G}}{k} \]  

(27)

where \( Q_{t}^{P2G} \) and \( P_{t}^{P2G} \) are the gas consumption and electricity consumption in period \( t \), respectively, and \( \eta_{P2G} \) is the electricity-to-gas efficiency.

(7) Electric boiler unit output constraint is as follows:

\[ H_{t}^{EB} = P_{t}^{EB} \eta_{EB} \]  

(28)

where \( H_{t}^{EB} \) and \( P_{t}^{EB} \) are the heat supply and electricity consumption of the electric boiler in the \( t \) period, respectively; \( \eta_{EB} \) is the conversion efficiency of electric heating.

### 6. Case Analysis

Considering that the existing linear constraint solving algorithm is relatively mature, this paper calls the YALMIP solver based on the MATLAB platform to solve it. The model proposed in this paper is simulated and verified based on the operation data of the integrated energy system in a region in southern China.

The renewable energy output curve and typical daily electricity, heat, and gas load curves of the integrated energy system are shown in Figures 2 and 3, respectively. The operating parameters, heating network pipeline parameters, and gas network parameters in the integrated energy system are shown in Tables 1, 2, and 3.

In order to verify the effectiveness of the proposed model, two cases are proposed for comparative simulation.

**Case 1:** The traditional optimized operation method is adopted, without considering the dynamic characteristics of the heating network and the gas network.

**Case 2:** The operation method proposed in this paper is adopted, and the dynamic characteristics of the heat network and the gas network are considered.

In the two cases, through the output of energy production equipment, energy conversion equipment, and energy storage device, under the premise of ensuring the operational reliability of the system, the various costs of the system are obtained as shown in Table 4.

It can be seen from Table 4 that the total cost of Case 2 is 32.08% lower than that of Case 1. Among them, the gas
purchase cost of case 2 is 26.60% lower than that of Case 1. Under the premise of the same heat load demand, the more accurate modeling method for the transmission delay in Case 2 reduces the gas purchase cost and maintenance cost of the heating system, so that the total operating cost can be reduced. Under the premise of the same gas load demand, Case 2 reduces the gas purchase cost and maintenance cost of the gas supply system, which reduces the total operating cost. The heat purchase cost of Case 2 is 21.04% lower than that of Case 1. This is because after considering the energy inertia of the heat network, the heat network can store thermal energy in pipes and buildings through temperature, and then adjust it in real time according to the load demand, which can play the role of peak shaving and valley filling. In Case 2, thermal inertia and gas inertia are considered.

### Table 4: Operating costs for each case.

<table>
<thead>
<tr>
<th>Type</th>
<th>Case 1 [yuan × 10^4]</th>
<th>Case 2 [yuan × 10^4]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total operation and maintenance cost</td>
<td>93.82</td>
<td>68.17</td>
</tr>
<tr>
<td>Electricity purchase cost</td>
<td>66.21</td>
<td>43.46</td>
</tr>
<tr>
<td>Heat purchase cost</td>
<td>54.32</td>
<td>42.89</td>
</tr>
<tr>
<td>Gas purchase cost</td>
<td>44.88</td>
<td>32.94</td>
</tr>
<tr>
<td>Equipment cost per unit capacity</td>
<td>65.33</td>
<td>32.97</td>
</tr>
<tr>
<td>Total running cost</td>
<td>324.56</td>
<td>220.43</td>
</tr>
</tbody>
</table>

**Figure 4:** Gas inertial energy support curve.

**Figure 5:** Thermal inertia energy support curve.

**Figure 6:** Power grid equipment output curve of Case 1.

**Figure 7:** Heat network equipment output curve of Case 1.
comprehensively. The system can be optimized according to the characteristics of network energy conversion devices and energy storage, so the operating cost is the lowest.

The gas inertial energy support curve is shown in Figure 4. It can be seen that when the load demand increases, the flow near the load side at the end of the gas pipeline increases instantaneously, the gas transmission pipeline releases the pipe storage, and the pressure at the end decreases exponentially; when the load demand decreases, the flow near the load side at the end of the gas pipeline decreases instantaneously, the gas transmission pipeline is stored in the storage tube, and the pressure at the end increases negatively exponentially. The thermal inertial energy support curve is shown in Figure 5. It can be seen that when the heating system reduces the supply of heat energy, the heat load sacrifices the operating comfort, and the indoor temperature decreases exponentially; when the heating system increases the supply of less heat energy, the heat load returns to the operating comfort level, and the indoor temperature rises negatively exponentially.

Figures 6 to 11 are the system optimization results for the two cases. In Case 1, EB and P2G consume renewable energy generation, and CHP supplies energy normally. In Case 2, the CHP output is reduced because thermal inertia and gas inertia are considered. During the 10-h to 14-h period, the load increases, the output of CHP and GT increases, the heat storage equipment is charged, and the system operation flexibility is improved. In Case 2, CHP and GT participate in peak shaving during load peak hours. The heat storage device is charged at the moment of load valley. Therefore, the
CHP energy supply margin is increased, and the renewable energy consumption capacity is enhanced. At the same time, Case 1 consumes more gas than Case 2. Because the gas inertia is considered, the system purchases gas from 20 h to 6 h, and the gas storage equipment participates in peak shaving. Because the thermal inertia and gas inertia are considered, the CHP output is significantly reduced, and the system economy is improved.

The simulation results verify that considering the storage characteristics of the thermal system, the pressure characteristics of the gas pipeline network, and the storage characteristics of the gas pipeline can improve the regulation capability and economy of the system. Thermal inertia and gas inertia can provide energy regulation on multiple time scales for the system.

7. Conclusions

In this paper, the supporting role of the dynamic inertia of the thermal system and the gas system on the regulation capability of the integrated energy system is considered, and the inertial virtual energy storage models of thermal system and gas system are established, respectively, and an integrated energy system optimization model of thermal and gas inertia is proposed. Finally, an integrated energy system composed of an improved IEEE 30-node power system, 10-node thermal system, and 12-node gas system is used to simulate and verify the model proposed in this paper. The results show that:

(1) The thermal and gas inertias are considered to enable the thermal grid and the gas grid to have similar inertia to the power system, so that the strength of the electric-thermal-gas coupling is reduced.

(2) The thermal inertia and gas inertia in the integrated energy system have good adjustment ability and can provide energy support for the system on multiple time scales.

(3) Compared with the integrated energy system model that does not consider thermal and gas inertia, the system operation flexibility and economy can be improved by the synergistic complementarity of electricity, heat, and gas considering thermal and gas inertia.

Data Availability

The datasets generated for this study are available on request to the corresponding author.

Conflicts of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as potential conflicts of interest.

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