Key components of integrated energy system’s source side and their influence on integrated energy system

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Abstract. Integrated energy supply and emerging new energy is a sign of transformation of energy system for environmental protection. This paper firstly models the key components of source side in integrated energy system. On the one hand, this paper models integrated energy supply and energy conversion devices involving multiple energy systems, on the other hand, it models new energy which is rapidly growing, so that all of these energy supply methods can serve the coordinated dispatch of integrated energy system. Then this paper focuses on CHP with heat storage which is a typical energy supply method involving both integrated energy supply and energy conversion. Through case study, we find that the heat storage system can bring friendly interaction between heat and power system, enhance the flexibility of integrated energy system, and decouple complex integrated energy system, so as to improve the social economic welfare.

1. Introduction

Increasing the proportion of clean energy utilization is an important energy development strategy in China. The National Energy Administration of China has proposed that the proportion of non-fossil energy utilization should exceed 50% by 2050, and it is expected to achieve carbon neutrality by 2060. Therefore, improving the proportion of clean energy supply such as energy utilization efficiency and renewable energy has become vital. In China, traditional energy supply systems operate separately with poor coordination, and traditional heat and power supply often comes from the combustion of coal, and usually a production capacity device can only produce one form of secondary energy, which can no longer meet the requirements of a large number of renewable energy integration.

Integrated energy system which realizes coordinated operation of various energy forms is an important way to promote clean energy proportion and improve energy using efficiency [1]. The source side of the integrated energy system contains numerous components, firstly, a large range of equipment and energy storage devices make complex coupling relationship between energy flows, secondly, a large number of new energy technology booming participating in the supply of primary energy, but their energy conversion processes in the integrated energy system are unclear.

In an integrated energy system, integrated power sources such as CHP/CCHP induce a production coupling. The production efficiency can be effectively improved because the characteristics of different energy systems can be utilized to complement each other [1]. At present, clean heating is an effective method to guarantee the heating supply in northern China. The essence of this method is to transform
the traditional power station based on burning fossil fuels into thermoelectric generating unit. In this paper, modeling is carried out according to the characteristics of thermoelectric generating units and multi-energy flow conversion devices such as P2G devices. Heat storage system can provide more flexibility through transforming electrical energy into heat energy which is easy for storage. We regard heat storage system as a heating unit in heat system and as an electrical load in power system to model it.

With the increasing awareness of environmental protection, the search for safe, stable and low-cost new heat sources has become the focus of integrated energy system research. In recent years, the development and utilization of solar energy has become an important field in the global energy transformation. Accurate forecast of photovoltaic power generation output is of great significance to guarantee the security, stability and economic operation of the system after a high proportion of photovoltaic access. Terrestrial heat as clean energy, has also been popular in recent years. In this paper, the participation of solar energy and ground source heat pump in the energy supply process of integrated energy system are studied by using the mechanism modeling method, and the model is established.

Modelling various source side’s devices, according to their energy conversion and coupling characteristics for optimization of integrated energy system is of great significance, so as to improve the system's flexibility and stability as well as system energy’s utilization efficiency and assist in the consumption of distributed renewable energy to increase the proportion of renewable energy.

2. Models of integrated power supply devices
The characteristics of co-generation energy supply method determine that it has the advantages of low energy consumption and high output. Compared with traditional generators, coal-fired fuel oil and other methods, it can also output a part of electricity when it is used to generate heat for people. Statistics show that the use of cogeneration heating can greatly save a large amount of coal.

Co-generation involves multiple energy systems, so the modeling of this functional technology is of great significance for the optimization of integrated energy systems.

2.1. CHP/CCHP
CCHPs have refrigeration compared to CHP, so this section only describes the model of CCHP in detail. CCHP mainly uses gas turbine as shown in Fig 1 or gas internal combustion engine as shown in Fig 2 as the power supply equipment, and waste heat boiler and absorption refrigerating machine (such as lithium bromide unit) as the heat source and cold source. The configuration of the two co-supply systems is shown as Fig 1 and Fig 2.

The coupling relationship are shown as (1) and (2).

\[ a_f P_i (i) + b_f H_i (i) = F_i (i) \]  \[ H_i (i) = c_f P_i (i) + c_2 \]

Equation (1) represents the relationship between electricity output \( P_i (i) \), heat output \( H_i (i) \) and the input of natural gas \( F_i (i) \), while (2) represent the relationship between heat output and electricity output.

Model of waste heat boiler is shown as (3).

\[ Q_b = \eta_b Q_{br}; \eta_b = \eta_{br} \cdot \left( a_b + b_b \cdot \beta_b - c_b \cdot \beta_b^2 \right) \]

The first equation represents the relationship between the energy of output and input of waste heat boiler which depending on the units’ transforming efficiency.

Model of absorption refrigerating machine is shown as (4).
refrigerating machine:
\[
Q_c = \text{COP}_c \cdot Q_{c,\text{in}}, \quad Q_{c,\text{in}} \leq Q_c \leq Q_{c,\text{max}}; \quad \text{COP}_c = \text{COP}_{c,\text{ref}} \cdot \beta / (a_c \beta^2 + b_c \beta + c_c)
\]

heating machine:
\[
Q_h = \text{COP}_h \cdot Q_{h,\text{in}}, \quad Q_{h,\text{in}} \leq Q_h \leq Q_{h,\text{max}}; \quad \text{COP}_h = \text{COP}_{h,\text{ref}} \cdot \beta / (a_h \beta^2 + b_h \beta + c_h)
\]

In (4), the efficiency \( \eta_b \) and the equivalent coefficient \( \text{COP}_{c,\text{ref}} / \text{COP}_{h,\text{ref}} \) are always set as constants, the equations on the right only show how to get them from the coefficient of a specific unit.

Model of CCHP with gas turbine:
\[
\begin{align*}
    P_{GT} & = a_{E_{GT}} + b \\
    Q_{GT} & = p E_{GT} + q \\
    P_{GT,\text{in}} & = P_{GT,\text{max}} \left[ 1 - \frac{1}{2} \left( 1 - T_{T} / T_{G} \right) \right] \\
    P_{GT} & \leq P_{GT,\text{max}}
\end{align*}
\]

Model of CCHP with gas internal combustion engine:
\[
\begin{align*}
    P_{c} & = a_{E_{c}} + b \\
    Q_{c} & = p E_{c} + q \\
    Q_{fume} & = r E_{c} + s \\
    P_{c} & \leq P_{c,\text{max}}
\end{align*}
\]

\( P_{GT} / H_{GT} / E_{GT} \) present the electricity/heat output and the energy of natural gas input respectively. In (5), \( a, b, p, q \) are constants depending on units, and in (6), \( a, b, p, q, r, s \) are constants depending on units. The third equation represent the max output of gas turbine. \( Q_{\text{fume}} / Q_{\text{water}} \) present the output of fume and jacket water of gas internal combustion engine.

2.2. Thermal power plant with heat storage device
The heat storage boiler decouples the thermolectric system, which is not only conducive to deep participation in grid peak shaving, but also provides backup capacity to the grid. A typical heat storage boiler system is shown as Fig 3[2].

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Figure 1. CCHP with gas turbine
Figure 2. CCHP with gas internal combustion engine

Figure 3. A typical heat storage boiler system.
In modelling, there are assumptions as below:

$D_H$ is used to represent the equivalent heat load and the heat waste of the heat storage in the model is negligible. The heat storage boiler is regarded as a source in heat system and a load in electric system. The heat storage boiler model in the power system is shown in (7), and the model in heat system is shown in (8), where $P_S$ represents the output of the heat storage tank (positive means heat storage, while negative means heat release), and, respectively $P_{L_{\text{max}}}/P_{G_{\text{max}}}$ represent the power limits of the heat storage tank under heat storage and heat release states.

$$P_{H,H} = P_B \eta_B$$

(7)

$$P_S = \begin{cases} P_{L_{\text{max}}} & D_H < P_{H,H} \\ 0 & D_H = P_{H,H} \\ -P_{G_{\text{max}}} & D_H > P_{H,H} \end{cases}$$

(8)

### 2.3. P2G

The general relationship between the power consumed by P2G and the production of natural gas (methane) is shown as (9), where $f_{P2G}$ represents natural gas flow generated, and $P_p$ as power consumed, $\mu_p$ as the converting efficiency, $H_G$ as the calorific value of natural gas.

$$f_{P2G} = P_p \frac{\mu_p}{H_G}$$

(9)

### 3. Models of new productivity technology

At present, a new round of scientific and technological revolution and industrial transformation represented by emerging productivity technologies are on the rise, such as photovoltaic power, terrestrial heat energy and other fields.

Therefore, it is necessary to model energy conversion process based on their characteristics, so that they can be used in the optimal scheduling model in integrated energy system.

#### 3.1. Photovoltaic power generation

Output power of PV is represented as (10) and (11), where $P_{STC,PV}$ represents rated capacity of photovoltaic power generation, $G$ as actual gloss intensity, $T_{e,STC}$ as standard test conditions, $\gamma$ as temperature coefficient of photovoltaic power generation, $T_e$ as PV battery pack temperature, $\eta_{pv}$ as comprehensive efficiency of photovoltaic power generation, $\eta_{inver}$ as inverter efficiency, $\eta_{AC}$ as AC transmission efficiency and $\eta_{other}$ as efficiency after removal of unforeseen losses.

$$P_{pv} = P_{STC,PV} \eta_{pv} \frac{G_{STC}}{G} \left[1 + \gamma(T_e - T_{e,STC})\right]$$

(10)

$$\eta_{pv} = \eta_{inver} \eta_{AC} \eta_{other}$$

(11)

#### 3.2. Terrestrial heat

Low-temperature geothermal energy is mainly used for heating in two forms: direct utilization and cascade utilization. Direct utilization is directly connected to heat users, and then the tail water is recharged, or heat exchangers are used to exchange the water, which is separated from the user side, and
the cascade utilization uses a heat pump to improve the thermal energy grade of the geothermal tail water, so as to realize the full utilization of low-temperature geothermal water resources.

For the terrestrial heat pump system with the soil as the cold and heat source, not only the couplings between the internal parameters of the heat pump unit (CV2, CV3, CV4, CV5) are included, but also the couplings between the space parameters of the air conditioning end (CV1) and the heat pump unit as well as the underground circulating water parameters (CV6) should be considered.

In the heat pump unit, there are condenser which includes the condenser itself and evaporator, and the condenser itself which includes heat exchange processes CV2, CV3 is used for heat release, in other words, it serves the consumers’ cooling and heating system directly, so it has the heat exchange with the room CV1. Evaporator which includes heat exchange processes CV4, CV5 is used for heat absorption, so it exchange heat with soil and then transform the heat to the condenser, so that the heat can be used for consumers.

According to the first law of thermodynamics and the law of conservation of mass, the mathematical model of each control body is established. And according to the quasi-steady-state model to establish the mathematical equations of each control body. Heat exchange (HE) between room and outdoor is shown as (12), HE between the room and the end of the air conditioner is shown as (13), HE between the water side of the condenser and the working fluid side of the condenser is shown as (14), and HE between the water side of the evaporator and the working fluid side of the evaporator is shown as (15).

\[ G_c C_p (t_{co} - t_{ci}) = K_h A_h (t_i - t_o) \]  
\[ G_c C_p (t_{co} - t_{ci}) = K_p F_p \frac{t_{co} - t_{ci}}{\ln \frac{t_{co} - t_i}{t_{ci} - t_i}} \]  
\[ G_c C_p (t_{co} - t_{ci}) = K_c F_c \frac{t_{co} - t_{ci}}{\ln \frac{t_{ci} - t_i}{t_{ci} - t_i}} \]  
\[ G_c C_p (t_{co} - t_{ci}) = K_e F_e \frac{t_{ci} - t_{co}}{\ln \frac{t_{ci} - t_e}{t_{co} - t_e}} \]

Figure 4. Coupling relationship and control volume diagram of ground source heat pump system[4]
4. Increasing the flexibility of combined heat and power system through optimal dispatch considering heat storage

As we have discussed before, there are various source side devices, and we want to see what benefit will they bring to the combined heat and power system. Here we use simulation to test the flexibility the heat storage device brings to the system.

We use an example in two scenarios (the first without heat storage and the second one with it at node1) as fig 4-1 shown. The dispatch framework and its optimization model pick up where we left off in last research[5].

![Figure 5. Combined heat and power system](image)

4.1. Case study

(1) Scenario without heat storage device

Total cost=$ 225612.3603

The power output is shown in Figure 6 and figure 7.

(2) Scenario with heat storage device

Total cost=$ 225567.9478

The power output is shown in Figure 8 and figure 9.

The combined heat and power system improves the flexibility of their respective systems because of the friendly interaction through heat storage.

![Figure 6. Power output of CHP1 in scenario 1](image)

![Figure 7. Power output of CHP1 in scenario 2](image)

Fig 6 and Fig 7 present the generating states when none of them have heat storage device, while Fig 8 and Fig 9 present when CHP 1 has heat storage device and CHP 2 does not have one.

Heat load and electricity load have the opposite changing trend, because during winter the heat load is always high while electricity load is low at night, and the heat load is always lower while electricity load is always higher in the daytime. In scenario 1, both in CHP1 and CHP2 the generation of heat and electricity have opposite trends as the heating load and electricity load.
Then we do 2 comparations in simulation results to know the influence heat storage device have on the coupled generation.

Firstly, thermoelectric decoupling is carried out, which fully alleviates the production contradiction of the electric and heating load curve with opposite shape. Comparing Fig 6 and Fig 7, in Fig 6, CHP1 without heat storage device have opposite trends of heat and electricity output which is the same as the load curve, while in Fig 7, CHP1 with the device have the same trends of heat and electricity output. The reason for that is the device transform heat load to electricity load, so that the operation constraint of heat and electricity output is decoupled. Comparing Fig

Secondly, the total energy supply cost are shown, it can be seen that the heat storage device can reduce total generation cost. That is because when heat generation has higher cost, the heat storage device gives CHP a choice to generate electricity with lower cost to produce heat in the device.

5. Conclusions
Modelling source side’s key components of different energy system for constraints to optimization control of the integrated energy system and collaborative optimization scheduling, the operating efficiency of the multi-energy flow system can be further improved, and complementarity of the integrated energy system can be promoted, and carbon emissions can be further reduced.

At the same time, this paper studies the influence of CHP unit with heat storage system to the scheduling of the integrated energy system, and finds that it can effectively decouple the integrated energy system and improve the economic benefits of the system.

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References
[1] Qin X, Guo Y, Shen X, et al. Increasing the Flexibility of Combined Heat and Power Systems through Optimal Dispatch with Variable Mass Flow Rate[J]. 2020.
[2] Nayef D S, Hollis I A. Electric power plant with thermal storage medium[J]. EP, 2012.
[3] Xza B, Yza B. Environment-friendly and economical scheduling optimization for integrated energy system considering power-to-gas technology and carbon capture power plant[J]. Journal of Cleaner Production, 2020, 276.
[4] Shonder, John A, Martin, Michaela A, McLain, Howard A, & Hughes, Patrick. Comparative Analysis of Life-Cycle Costs Of Geothermal Heat Pumps And Three Conventional HVAC Systems. United States.
[5] Xie, P., Mao, T., Peizheng, X., Zou, J., & Lu, S. (2021). Integrated pricing mechanism for combined electric and heat systems considering heat time delays.