Optimal Operation Strategy of Multi-energy System

Yanmei Tang¹, Kecheng Li¹, Shanyou Wang¹ and Lu Jin¹

¹China Electric Power Research Institute, Beijing, China

*Corresponding author e-mail: zzz@zzz.com

Abstract: Multiple energy system could meet the needs of the user through different energy conversion ways. So if the load level is constant, the operating state of energy system could be different to meet different demand. By the analysis of energy flow of system, it can be known that the degrees of freedom come from the dispatch point of energy flow. Therefore, the dispatch factors and the input energy flows could be considered as the independent variables, and make a comprehensive evaluation criterion which considered the energy efficiency, economy and emission, as the optimization goal. The operation of the multi-energy flow system has been optimized. Through case analysis, the proposed optimal energy flow operation strategy was verified and analysed.

Keywords: Multi-Energy System, Energy Hub, Operation Strategy, Nonlinear Optimization, Typical Day Analysis

1. Introduction

With the gradual depletion of fossil energy, changes in energy structure are imminent [1, 2]. The concept of multi-energy system and energy internet is proposed to solve the problems of uneven storage and uneven distribution of primary energy [3]. Firstly, the multi-energy system plans the use of different energy sources such as cold, heat, electricity, and gas; it considers the cost of different energy sources, and uses multi-energy complementary methods to rationally use primary energy while ensuring the balance between energy supply and demand. Moreover, the energy internet interconnects decentralized multi-energy systems, making it possible for distributed energy systems, especially userside energy systems. The user-side energy system has a good ability to absorb renewable energy. Therefore, the construction of the energy Internet is of great help to improve the utilization rate of renewable energy [4-6].

The concept of energy hub [7] plays a key role in the research of multiple energy systems and energy internet. The concept of energy hub comes from a very simple idea: no matter how complex a multi-energy system is, no matter how complicated the conversion processes between cold, heat, electricity, and gas is, it requires various forms of energy input and outputs various forms of energy to the corresponding energy network or energy users. Based on this consideration, a multi-energy system can be abstracted into a “black box” with input and output ports, and this abstract mathematical model becomes an energy hub [8]. With the help of the concept of an energy hub, it is convenient to construct an energy internet and study the energy trends therein.
At present, the research on multi-energy systems and energy internet based on energy hub mainly focuses on two aspects: first, the optimal configuration of energy hub [9, 10]; second, the optimal operation of energy hub [11, 12]. The key to the optimal configuration of energy hub is what kind of equipment should be selected in the energy hub and how much capacity should be used to achieve the goal to meet the energy demand and make the lowest cost [13]. Existing researches have discussed the configuration of energy hubs in detail for different types of energy users (such as schools, office buildings, hotels, etc.) and usage scenarios. The optimization operation of the energy hub mainly involves the selection of optimization goals. According to different optimization objectives, the researchers have proposed different evaluation systems to evaluate the operation status of the energy hub.

This article will study the optimization operation and configuration of multi-energy systems from the concept of energy hub, and compare the optimized operation method with traditional methods through specific examples to illustrate its superiority.

2. System Matrix Modelling

The energy conversion process of the multi-input multi-output energy hub can be implemented by a single device or by multiple devices, but we do not consider the interior of the energy hub when modeling the specific structure of the project and only treats the energy hub as a whole “black box”.

Various forms of energy from input to output can be divided into two steps: energy distribution and energy transmission or conversion. Energy distribution refers to the distribution of various energy sources to different energy transmission or conversion equipment in a certain proportion. Energy transmission or conversion refers to the conversion of energy into the equipment through mechanical, chemical and other means, with certain conversion efficiency. The structure of the multi-energy system studied in this paper is shown in Figure 2.

![Figure 1. The model of multi-energy system implemented.](image)

2.1. Efficiency Matrix of Equipment

The efficiency matrix of the equipment mainly describes the energy conversion efficiency of the energy conversion equipment in the multi-energy system. In this paper, the input and output vectors of the equipment in the multi-energy system are defined, as shown in equation (2).

\[
\begin{align*}
\mathbf{v}'_i &= \begin{bmatrix} F'_i & E'_i & Q'_{c,i} & Q'_{h,i} \end{bmatrix}^T \\
\mathbf{v}'_o &= \begin{bmatrix} F'_o & E'_o & Q'_{c,o} & Q'_{h,o} \end{bmatrix}^T
\end{align*}
\]

In the rest of this article, the order of the elements in the input and output vectors is the same as equation (2), where F represents natural gas, E represents electricity, Qc represents the cold energy, Qh represents the heat energy. Therefore, the input vector and output vector of the ith device can be linked...
by the efficiency matrix of the device, as shown in equation (3), where the efficiency matrix of the first device is represented as $H^i$.

\[ v_o^j = H^j v_i^j \]  

(2)

In this paper, the power generation efficiency of the power generation unit is $\eta_{pg\text{,e}}$ and the heat production efficiency is $\eta_{pg\text{,h}}$, then the input and output of the cogeneration unit can be described as:

\[
\begin{bmatrix}
0 \\
E_{pg}^{\text{in}} \\
0 \\
Q_{pg}^{\text{in}}
\end{bmatrix} = \begin{bmatrix}
\eta_{pg\text{,e}} & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
\eta_{pg\text{,h}} & 0 & 0 & 0
\end{bmatrix} \begin{bmatrix}
E_i^{\text{in}} \\
0 \\
0 \\
0
\end{bmatrix} = H^{pg\text{,in}} v_i^{pg\text{,in}}
\]

(3)

The construction rules of the efficiency matrix are as follows: since the input and output matrices are all $4 \times 1$ column vectors, the efficiency matrix of each device is $4 \times 4$ matrix. The element in the $i$th row and $j$th column of the matrix corresponds to the efficiency of the equipment to convert $j$th kind of energy to $i$th kind of energy. Therefore, the efficiency matrix of the other equipment should be:

\[
\begin{align*}
H^i &= \begin{bmatrix}
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & \eta_e & 0 & 0
\end{bmatrix} \\
H^o &= \begin{bmatrix}
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & \eta_o
\end{bmatrix} \\
H^m &= \begin{bmatrix}
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & \text{COP}_m
\end{bmatrix} \\
H^{pg\text{,in}} &= \begin{bmatrix}
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & \text{COP}_{pg\text{,in}}
\end{bmatrix}
\end{align*}
\]

(4)

2.2. Dispatch Matrix of Equipment
As mentioned above, the system's energy input to output go through two steps, energy distribution and energy conversion. The efficiency matrix describes the performance of energy conversion within the equipment, and the dispatch matrix represents the energy flow distribution between the equipment in the system. In addition, the distribution factor only exists at the bifurcation of the system, which is indicated by the red circle in Figure 1. The natural gas input from outside the system needs to be distributed to the combined heat and power unit and gas boiler. Therefore, the allocation matrix of each equipment can be constructed, and the system input and equipment are connected through the allocation matrix, as shown in equation (5) is the allocation matrix of the cogeneration unit.

\[
\begin{bmatrix}
\alpha_{pg\text{,in}} & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0
\end{bmatrix} \begin{bmatrix}
E_m \\
E_{\text{grid}}
\end{bmatrix} = \Gamma^{pg\text{,in}} v_i^{pg\text{,in}}
\]

(5)

The construction rules of the dispatch matrix are as follows: since the input and output matrices are all $4 \times 1$ column vectors, the efficiency matrix of each device is $4 \times 4$ matrix. The element in the $i$th row and $j$th column of the matrix corresponds to the dispatch factor of the system input $j$th kind of energy to equipment input $i$th kind of energy. Therefore, the efficiency matrix of the other equipment should be:
\[
\Gamma^b = \begin{bmatrix}
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
\alpha_{ps} \eta_{ps,b} + \alpha_{h} \eta_{h} & 0 & 0 & 0
\end{bmatrix}
\]
\[
\Gamma^s = \begin{bmatrix}
\alpha_s & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0
\end{bmatrix}
\]
\[
\Gamma^{ac} = \begin{bmatrix}
\alpha_{ps} \eta_{ps,b} + \alpha_{h} \eta_{h} & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
\end{bmatrix}
\]

In summary, corresponding to the three bifurcation points in Figure 2, there are six dispatch factors that are not independent of each other.

2.3. Conversion Matrix of System

The conversion matrix of the entire multi-energy system describes the efficiency of each component and the entire energy flow process of the system. The operating strategy of the system is also inherently included in the conversion matrix by means of the dispatch factors. First, define the input of the system as:

\[
v_i = F_m \ E_{grid} \ Q_{c,j} \ Q_{h,j} = F_m \ E_{grid} \ 0 \ 0 \]

(7)

Similarly, the output of the system is defined as:

\[
v_o = F_o \ E_{user} \ Q_{c,o} \ Q_{h,o} \]

(8)

Assuming that the conversion matrix of the system is \(H\), the energy conversion process of the system can be written as:

\[
v_o = Hv_i
\]

(9)

In summary, the conversion matrix of the available system is:

\[
H = \begin{bmatrix}
0 & 0 & 0 & 0 \\
\alpha_{user} \eta_{ps} + \alpha_{h} \eta_{h} & 0 & 0 & 0 \\
\alpha_{user} \eta_{ps} \eta_{ps,b} + \alpha_{h} \eta_{h} \eta_{h,b} & 0 & 0 & 0 \\
\alpha_{user} \eta_{ps} \eta_{ps,b} \eta_{ps,b} + \alpha_{h} \eta_{h} \eta_{h,b} \eta_{h,b} & 0 & 0 & 0 \\
\end{bmatrix}
\]

(10)

The main goal of this paper is to determine the dispatch factors and system inputs to make the system run optimally.

3. Optimization

3.1. Evaluation Criteria

The operation of the system needs to be optimized according to a certain evaluation criterion. In this paper, the evaluation criterion of the system operation is considered from three aspects of comprehensive energy efficiency, economic benefit, and carbon emissions.

The comprehensive energy efficiency of a multi-energy system is defined as the ratio of the total demand for cold, heat, electricity and gas at the output to the input of fossil energy. In the calculation process, each energy needs to be converted into standard coal quality.

\[
\eta_{total} = \frac{Q_{c,eq} + Q_{h,eq} + E_{user,eq}}{F_{m,eq} + E_{grid,eq}}
\]

(11)
In the formula, $Q_{c,o,eq}$, $Q_{h,o,eq}$ and $E_{user,eq}$ respectively represent the standard coal equivalent of the total consumption of cold, heat, and electricity at the user side (system output); and $F_{m,eq}$, $E_{grid,eq}$ represent the standard coal equivalent of the input energy.

The economic benefit of system operation are related to the electricity price of the power grid, the price of natural gas, and the price of the energy productions to be provided to users. The electricity price of electricity sold by the grid adopts the peak-valley time-sharing electricity price policy, that is, the peak electricity price is raised by 70% during peak hours, 50% during peak hours, and -50% during low hours. The price of natural gas and the price of providing energy services to users are basically unchanged. In order to standardize the economic efficiency indicators, a reference system needs to be selected. In this paper, the user's power demand is directly satisfied by the power grid, the heating demand is directly satisfied by the gas boiler, and the cooling demand is directly satisfied by the electric refrigerator. Then the operating income of the sub-supply system under the same demand can be estimated, so as to obtain the economic benefit criterion $C_e$:

$$C_e = \frac{C_{c,o} + C_{h,o} + C_{e,eq} - C_{e,grid} - C_f}{C_{c,o,eq} + C_{h,o,eq} - C_{e,grid,eq} - C_{f,eq}}$$

Where $C_{c,o}$ represents the income from supplying cooling to users, $C_{h,o}$ represents the income from supplying heat to users, $C_{e,eq}$ represents the income from supplying electricity to users, $C_{e,grid}$ represents the cost of purchasing electricity from the grid, and $C_f$ represents the cost of purchasing natural gas from the grid.

The idea of estimating carbon energy is to multiply the consumed input energy by the corresponding carbon emission coefficient to obtain the quality of carbon dioxide emitted.

$$CDE = E_{grid} \mu_e + F_m \mu_f$$

Similarly, in order to standardize the carbon emission index, the sub-supply system is selected as a reference to estimate the carbon emission of the sub-supply system under the same demand, thereby obtaining the carbon emission criterion $CDER$.

$$CDER = \frac{E_{grid,eq} \mu_e + F_{m,eq} \mu_f}{E_{grid,eq} \mu_e + F_{m,eq} \mu_f}$$

To measure the operating status of a multi-energy system, the above three indicators need to be considered together, and the three indicators need to be weighted and converted into smaller and better indicators, as shown in equation (15).

$$EC = -\omega_1 \eta_{total} - \omega_2 C_e + \omega_3 CDER$$

3.2. Explanation of Optimization Problem

The optimization of the entire multi-energy system includes the following three aspects of work: 1) optimizing the dispatch factors; 2) optimizing the input energy; 3) optimizing the equipment capacity. The optimization of the internal distribution factor of the system is to coordinate the energy flow distribution of the system, so that the system can minimize the objective function under the condition of meeting the demand. The input energy of the optimized system is to purchase a reasonable amount of electricity and natural gas to meet user needs and minimize the objective function. The capacity of each device in the system is also a key factor for optimization. The optimized distribution factor and input energy are based on the capacity of the system. The capacity of the system should not be too small, otherwise it will be unprofitable, and it should not be too large because the excessive installed capacity makes the cost higher.

In the previous article, 6 distribution factors were proposed, but they are not independent of each other. It is necessary to reduce the 6 distribution factors to 3 independent distribution factors, plus the
system has 2 inputs, so the system optimization has 5 independent variables. That is to find the optimal value of the objective function by changing the values of 5 independent variables.

4. Case Study
Solving the above optimization problems requires nonlinear programming techniques. This paper uses the sequential quadratic programming method, which can handle nonlinear constraints with multiple variables. Table 1 gives the capacity or efficiency parameters of each device in the case studied.

| Equipment          | Capacity | Efficiency          |
|--------------------|----------|---------------------|
| Power generation unit | 1000 kW  | $\eta_{pgu,e}=0.3$, $\eta_{pgu,h}=0.5$ |
| Gas boiler         | 900 kW   | $\eta_h=0.8$        |
| Electric chiller   | 400 kW   | COP$_{ac}=3$        |
| Absorption chiller | 400 kW   | COP$_{ac}=0.7$      |
| Heat unit          | 1000 kW  | $\eta_h=0.9$        |

Three typical day characteristics were selected for the user load, which are the typical day in the summer cooling period, the typical day in the winter heating period, and the typical day in the transition period. The user load for three typical days is shown in Figure 3.

![User Load](image_url)

**Figure 2.** Hourly electricity, heat and cooling load patterns for typical days

First consider the weights in the comprehensive evaluation index equally, that is, make $\omega_1 = \omega_2 = \omega_3 = 1/3$. The optimization results of the typical winter operation are shown in Figure 6. First, we can get the typical daily user load characteristics in winter from Figure 2, that is, there is no cold load demand, and there are electric load and heat load demand throughout the day, the load peak during the day and the load valley at night. Based on this characteristic, the optimized operation result is that the electric load at night is mainly satisfied by the power purchase of the power grid, and the heat load is mainly satisfied by the gas boiler; the electric load and the heat load during the day are higher, so the
electric load is mainly produced by cogeneration. The unit is satisfied, and the part with insufficient heat load demand is supplemented by the gas boiler. The optimization goal is to purchase a small amount of natural gas at night, and the natural gas is mainly supplied to the gas boiler, and a large amount of natural gas is purchased during the day. The share allocated to the cogeneration unit makes its power generation meet the needs of users.

Similarly, the optimized operation results of the transition period and the typical summer days can be obtained, as shown in Figures 4. The characteristics of the transition period are similar to the typical winter days, except that the heat load level generally decreases, and there will be a small amount of cold load during the day. From the optimized operation results, due to the low cooling load level at night during the transition period, it can be mainly satisfied by the gas boiler, but not by the cogeneration unit. At the same time, the cogeneration unit can also meet the electrical load. The cooling load, and because the cooling load is too low, is mainly satisfied by the electric refrigeration unit.

The characteristic of a typical day in summer is that the heat load and the cooling load have a considerable level during the day, and they are also load valleys at night. From the optimized operation results, since there is only electricity load demand at night, it can be directly met by the grid to purchase electricity. The electric load is met by the cogeneration unit. At the same time, the power generation of the cogeneration unit is mainly used to meet the electric load, and a small amount is used for the electric refrigeration unit. The unit provides cooling capacity, and the energy saving of the absorption refrigeration unit is reflected.

![Optimized operation results for typical days](image)

**Figure 3.** Optimized operation results for typical days

5. **Conclusion**

This paper builds a multi-energy system through an energy hub model, and describes the multi-energy system as a system conversion matrix, equipment conversion matrix, equipment efficiency matrix, and equipment allocation matrix. The process of optimizing the operation of a multi-energy system
through the energy hub model is elaborated in detail. It mainly includes two parts: 1) a comprehensive evaluation index that takes into account three factors such as energy efficiency, economy, and carbon emissions through linear weighting. The index is used as the optimization goal; 2) the modeled energy hub is used as the nonlinear equality constraint of the optimization problem, and the capacity and operating characteristics of the equipment are used as the inequality constraint of the optimization problem. The sequential quadratic programming algorithm is used to solve the optimization problem, and the hourly user load is taken as input to obtain the hourly system optimization operation strategy.

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