Robust Optimization of Multiple Microgrids Scheduling for Integrated Energy System with Uncertain Sources and Loads

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Abstract. With the rapid development of integrated energy system and microgrid technologies, aiming at the operational safety problems caused by the uncertainty of the sources and loads, this paper proposed a robust optimal scheduling model of the multiple integrated energy microgrids considering sources and loads uncertainty. In order to minimize the total operating cost of the multiple microgrids, the interconnection lines were introduced into the multiple microgrids for joint operation, on the basis of renewable energy outputs and multi-energy loads prediction, the uncertainty of sources and loads were characterized and the established model were solved. The results of an example showed that the proposed method can effectively improve the economy of multiple microgrids and reduce the risk caused by the uncertainty of sources and loads, thus verified the effectiveness and feasibility of the proposed method.

1. Introduction
In 2019, the State Grid proposed a strategic goal for energy development, which indicated the direction of future energy development. The integrated energy system deeply couples various forms of energy flow such as cold, heat, electricity, and gas through energy conversion equipment, and realizes the complementarity between energy flows, which can effectively promote the absorption of renewable energy, and realize the cascade utilization of energy. Therefore, the development of an integrated energy system is of great significance for promoting energy development. At present, most studies are based on the operation of a single integrated energy microgrid [1, 2], and there are few studies on the economic operation of multiple microgrids. In practice, on the basis of considering the uncertainty of the outputs of renewable energy [3], the interconnected operation mode is adopted for the energy system can effectively realize the energy interaction between various integrated energy microgrids and improve the safety and reliability of microgrids [4]. Therefore, it is of great practical significance to study the economic optimization operation of multiple integrated energy microgrids (MIEM) under the condition of uncertain sources and loads.

Aiming at the safety and reliability problems caused by the uncertainties of renewable energy outputs and multi-energy loads, this paper proposes an optimization operation method that takes into account the uncertainty of sources and loads for multiple microgrids. In this paper, interconnection lines are used to interconnect MIEM [5], on the basis of renewable energy outputs and multi-energy loads forecast data, the interval description method is used to characterize the uncertainty of sources
and loads, and then a robust constraint is formed. Taking the minimum operating cost of the MIME system as the objective function, a scheduling model is established and solved, and the results show the rationality and feasibility of the proposed method.

2. Structure Of MIEM and Model of Equipment

2.1. Structure of MIEM
The MIEM system constructed in this paper contain four types of energy sources: cold, heat, electricity, and gas. Each microgrid can interact with each other through interconnected lines. The schematic diagram is shown in figure 1.

![Figure 1. Structure diagram of MIEM.](image)

It can be seen from the figure that the system can purchase electricity, heat and gas from the external energy network, and the outputs of fans and photovoltaics provides part of the load demand as renewable energy. In order to realize the multi-energy complementary and integrated characteristics of the integrated energy system, a variety of energy conversion equipment are provided inside the system, including cogeneration units (CU), gas boilers (GB) and so on. When renewable energy and interconnected lines cannot provide the full load of the microgrid, the external energy network will make up for it. The conversion process of energy conversion equipment is irreversible, and the energy of the microgrid cannot be sold to the energy network.

2.2. Modeling of Energy Conversion Equipment

2.2.1. Modeling of Cogeneration Unit

\[ P_{chp} = \eta_c L_{NG} v_{chp} \]  \hspace{1cm} (1)

\[ P_{hsp} = \eta_h L_{NG} v_{chp} \]  \hspace{1cm} (2)

where \( P_{chp}, H_{chp} \) are outputs of electric power and heating power respectively; \( v_{chp} \) is the natural gas consumption rate; \( L_{NG} \) is the low calorific value of natural gas; \( \eta_c, \eta_h \) are the power generation efficiency and heat generation efficiency, which are 0.3 and 0.56 respectively.
2.2.2. Modeling of Absorption Chiller. The absorption chiller (AC) uses the heating energy generated by the cogeneration unit for refrigeration, and the expression is:

$$C_{AC} = H_{AC} \eta_{AC}$$ (3)

where $C_{AC}$ is the output cooling power; $H_{AC}$ is the heating power consumed; $\eta_{AC}$ is the cooling coefficient, equal to 1.2.

In addition, the efficiency of the electric boiler (EB) and gas boiler in the system are both 0.9, and the energy efficiency ratio of the electric refrigeration (ER) equipment is 3.

3. Optimal Scheduling Model Considering Uncertainty of Sources and Loads

3.1. Objective Function

This article aims at the minimum comprehensive cost of MIEM, which is specifically expressed by the following formula:

$$\min C_{\text{total}} = C_{\text{buy}} + C_{\text{op}}$$ (4)

where $C_{\text{total}}$ is the daily comprehensive cost of multiple microgrids, consisting of energy purchase cost and operating cost.

$$C_{\text{buy}} = \sum_{i=1}^{n} \sum_{t=1}^{T} \left( c_{i}^e P_{i,\text{grid}}(t) + c_{i}^g V_{i,\text{gas}}(t) + c_{i}^h H_{i,\text{heat}}(t) \right)$$ (5)

$$C_{\text{op}} = C_{\text{pol}} + C_{\text{ab}} + C_{\text{con}}$$ (6)

$$C_{\text{pol}} = \sum_{i=1}^{n} \sum_{j=1}^{m} C_{j,\text{pol}} F_{j,\text{pol}}$$ (7)

$$C_{\text{ab}} = \sum_{i=1}^{n} \sum_{t=1}^{T} \alpha P_{ab}(t)$$ (8)

$$C_{\text{con}} = \sum_{i=1}^{n} \sum_{t=1}^{T} \left( a P_{\text{con}}(t) + b H_{\text{con}}(t) \right)$$ (9)

where equation (5) & (6) represent the system's energy purchase cost and operating cost separately; equations (7) to (9) reflects the items in the operating cost, which are the environmental translation cost, the abandoned electricity cost and the cost paid to the interconnection line; $c_{i}^e, c_{i}^g, c_{i}^h$ are the price of electricity, gas and heating at time $t$; $P_{i,\text{grid}}(t), V_{i,\text{gas}}(t), H_{i,\text{heat}}(t)$ are the electricity, gas and heating purchase of microgrid $i$ at time $t$; $C_{j,\text{pol}}$ is the unit penalty cost of pollutant $j, E_{j,\text{pol}}$ is the emission of pollutant $j; \alpha$ is the unit cost of abandoned electricity, $P_{ab}(t)$ is abandoned power; $a, b$ are the unit cost of passing through the power interconnection lines and the heat interconnection pipelines respectively; $P_{\text{con}}(t), H_{\text{con}}(t)$ are the electric power and heat power passing through the power interconnection lines and the heat interconnection pipelines at time $t$.

3.2. Constraint Condition

3.2.1. Constraints of Energy Flow

$$P_{i,\text{Load}} = P_{i,\text{PV}} + P_{i,\text{WT}} + P_{i,\text{grid}} + P_{i,\text{ER}} - P_{i,\text{EB}} - P_{i,\text{con}}$$ (10)

$$H_{i,\text{Load}} = H_{i,\text{heat}} + H_{i,\text{EB}} + H_{i,\text{GM}} + H_{i,\text{ER}} - H_{i,\text{AC}} - H_{i,\text{con}}$$ (11)

$$C_{i,\text{Load}} = C_{i,\text{ER}} + C_{i,\text{AC}}$$ (12)
where $P_{\text{Load}_i}$, $H_{\text{Load}_i}$, $C_{\text{Load}_i}$ are the electric load, heating load and cooling load of microgrid $i$; $P_{\text{con}_i}$, $H_{\text{con}_i}$ are the electric power and heating power transmitted by the contact line of microgrid $i$. Since microgrids satisfy the constraints of formulas (10) to (12) at any time, $t$ in the formulas are hidden.

### 3.2.2. Constraints of Equipment Output

To simplify the constraints, assuming that $A$ is the outputs of the equipment, then there is:

$$A_{\text{min}} \leq A \leq A_{\text{max}}$$  \hspace{1cm} (13)

where $A_{\text{min}}$, $A_{\text{max}}$ are the lower and upper limit of the output of each energy conversion equipment.

### 3.2.3. Constraints of Energy Purchase

$$\begin{align*}
0 & \leq P_{\text{grid}_i}(t) \leq P_{\text{grid}_i}^{\text{max}} \\
0 & \leq H_{\text{heat}_i}(t) \leq H_{\text{heat}_i}^{\text{max}} \\
0 & \leq V_{\text{gas}_i}(t) \leq V_{\text{gas}_i}^{\text{max}}
\end{align*}$$  \hspace{1cm} (14)

where $P_{\text{grid}_i}^{\text{max}}$, $H_{\text{heat}_i}^{\text{max}}$, $V_{\text{gas}_i}^{\text{max}}$ are the maximum values of electricity purchase, heating purchase, and gas purchase of microgrid $i$.

### 3.2.4. Constraints on the Transmission Power of Interconnected Lines

$$\begin{align*}
-P_{\text{con}_i}^{\text{max}} & \leq P_{\text{con}_i} \leq P_{\text{con}_i}^{\text{max}} \\
-H_{\text{con}_i}^{\text{max}} & \leq H_{\text{con}_i} \leq H_{\text{con}_i}^{\text{max}}
\end{align*}$$  \hspace{1cm} (15)

When $P_{\text{con}_i}$ or $H_{\text{con}_i}$ is positive, it means that the microgrid $i$ transmits energy outward, otherwise it accepts energy from other microgrids.

### 3.3. Robust Optimization Model

There are uncertainties in the sources and loads prediction during the operation of MIEM, which will be considered when establishing a robust optimization model in this paper. The uncertain sets are used to characterize the uncertainty of sources and loads [6], that is, for loads and renewable energy outputs, both meet: $L \in T_L$, $S \in T_S$.

This article uses interval characterization to describe uncertain sets:

$$L_f - L_u \leq L \leq L_f + L_u$$  \hspace{1cm} (16)

$$S_f - S_u \leq S \leq S_f + S_u$$  \hspace{1cm} (17)

where $L_f$, $S_f$ are the predicted multi-energy loads and renewable energy outputs; $L_u$, $S_u$ are the corresponding maximum uncertain values.

The following formulas are used to equate formulas (16) & (17):

$$L = L_f (1 \pm \epsilon_L)$$  \hspace{1cm} (18)

$$S = S_f (1 \pm \epsilon_S)$$  \hspace{1cm} (19)

where parameters $\epsilon_L$, $\epsilon_S$ represent the uncertainty of multi-energy loads and renewable energy outputs in the microgrid.

Through the description of uncertainty parameters, the corresponding range of multi-energy loads and renewable energy outputs can be obtained.
4. Analysis of Examples

4.1. Example System Settings

Based on the multiple microgrids structure diagram built in figure 1, the multi-energy loads and renewable energy outputs of three microgrids in a certain area are predicted. Among the three microgrids, microgrid 1 is combined cooling heating and power, microgrid 2 is a distribution network with only photovoltaic power generation, and microgrid 3 is combined heating and power. Forecast data and TOU power price referenced literature [7], TOU heat price is shown in table 1, and the price of natural gas is 2.5 Yuan/m³. Taking into account various uncertain factors during the operation of the multiple microgrids, the uncertainty coefficient of the multi-energy loads is selected as ± 2.5% and the uncertainty coefficient of the renewable energy outputs is selected as ± 10% in this paper.

| Periods | Time          | Heat price (Yuan/(kW·h)) |
|---------|---------------|--------------------------|
| Peak    | 05:00—12:00   | 0.32                     |
|         | 17:00—22:00   |                          |
| Flat    | 12:00—17:00   | 0.28                     |
| Valley  | 22:00—24:00   | 0.20                     |
|         | 00:00—05:00   |                          |

4.2. Independent Operation Results

The lowest total operating cost of multiple microgrids is taken as the optimization goal when the system operates independently. Figure 2 shows the energy balance result of microgrid 1 in independent operation mode.

It can be seen from the figure 2 that when the electricity price and heat price are low, microgrids purchase electricity and heat from the energy network, and the microgrid 1 supplies the purchased excess electricity to the cooling load through the electric refrigeration equipment. Using natural gas for energy supply is more economical when the electricity price and heat price are high, microgrid 1 & microgrid 2 mainly purchase gas from the energy network and uses cogeneration unit to supply electric and heating loads. It can be seen from the results that in order to ensure economic efficiency, the microgrids try their best to avoid purchasing electricity and heat from the energy network when the electricity price and heat price are high, and since there is no energy support for each other, if there is a surplus of renewable energy after meeting all load requirements, the microgrids can only choose to abandon.

4.3. Operation Result of Interconnected Mode

Taking the upper limit of interconnected electric power as 300kW and the upper limit of interconnected heating power as 200kW as an example, the optimized operation results of each microgrid are obtained. Figure 3 shows the energy balance result of microgrid 1.
It can be seen from the results that when the output of renewable energy is high, the excess power will be transmitted to other microgrids through interconnection lines or use conversion equipment to provide other kinds of load, so as to reduce the energy purchase of the microgrid and improve economy. The same as when the microgrid operates independently, except that the microgrid 2 must purchase electricity from the energy network when the energy supply is insufficient, other microgrids purchase electricity and heat from the energy network mainly occurs when the electricity price and heat price are low, but for the rest of the time, they are seek power support from other microgrids or purchase gas from the energy network to meet load demand and ensure the economic operation of the system.

4.4. Influence of The Upper Limit of Interconnected Power
Assuming that the uncertainties of multi-energy loads forecasting are ±2.5% and renewable energy outputs forecasting are ±10%, the upper limits of interconnected power of electric power communication lines and thermal communication pipelines are discussed. Figure 4 is the multiple microgrids optimized operation result graph under different interconnected power upper limit.

It can be seen that as the upper limit of interconnected power increases, the operating cost of the system gradually decreases and eventually stabilizes. However, with the increase of the upper limit, the cost of constructing interconnection lines will also increase. Due to the limitations of the system’s load, the regulation effect of excessively high interconnection power limit is also limited. Therefore, in order to have a high regulation effect while ensuring economic operation, an appropriate interconnection power upper limit should be selected.

5. Conclusion
In this paper, the interconnection lines are introduced into the economic optimization scheduling model of MIEM, the cost of multiple microgrids independent operation mode is 19752 Yuan, and the cost of the method proposed in this paper is 15431 Yuan, and the economic benefit is increased by 21.9%. At the same time, the uncertainty of sources and loads prediction is considered in this paper, which ensures the robustness of the optimal scheduling strategy.
Selecting the appropriate upper limit of the transmission power of the interconnection line according to the scale of the multiple microgrids can ensure the flexible adjustment and economic operation of the system and reduce the construction cost of interconnection lines at the same time.

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