Integrated Energy Load Priority Scheduling Model Based on Customer Satisfaction

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Abstract. The integrated energy system is of great significance to improve the efficiency of social energy utilization, promote the large-scale consumption of renewable energy and the cascade utilization of energy. In view of the uncertainty of cooling, heating and electric load demand of users, this paper proposes a load priority supply model for integrated energy service providers, which considers the user satisfaction and the penalty function of energy supply interruption, and is used to deal with the scheduling optimization of various uncertain energy demand and translatable load. The optimal scheduling mathematical model of community integrated energy system is established. The various optimization objectives and the constraints of different energy demand are considered, the heuristic algorithm is used to solve the optimal scheduling, and the economic of operation mode is analyzed. The model can effectively reflect the impact of energy demand, user satisfaction and system cost on the priority of supply load, and provide the optimal decision to weigh the system cost and user satisfaction. The simulation results show the feasibility and effectiveness of the proposed model.

1. Introduction
High efficiency, clean and low carbon are the main trend of energy development in the world. At present, the energy shortage is becoming more and more serious, and the ecological environment is deteriorating. The concept of integrated energy system provides a new direction for the realization of environmental friendliness and energy sustainable development [1]. The Community Integrated Energy System (CIES) with the combined cooling heating and power (CCHP) system as the core and the "source-network-charge" coordination as the main feature is becoming a research hotspot.

So far, based on different optimization objectives and operation criteria, many scholars have carried out a lot of research on the optimal scheduling of integrated energy system. The main research takes the CCHP system as the main research object, establishes the objective function with the best economy, and optimizes the energy management of the CCHP system [2-3]. However, only the power supply side is optimized, which ignoring the autonomy of the load side. In paper [4], the concept, framework and model of demand response (DR) summarized, and the optimal operation and solution methods of DR are reviewed. Some researchers study the optimal scheduling method of integrated energy system under the premise of considering load-side DR [5-6]. In paper [7-8] propose to optimize the operation of distributed cooling and heating system considering the translational load on the user side, but the user comfort is not considered in the model. Most researches focus on the optimal operation of CIES, few people study the priority of cold and hot power supply based on the integrated energy service provider (IESP).
In this paper, based on the energy supply mode of IESP, an optimal scheduling mode of the load priority is proposed, which can meet the user comfort level. First of all, based on the supply priority of cooling, heating and power load priority, the energy supply model and the interruption penalty function considering the user satisfaction are designed. Then, an optimal scheduling method of the CIES including renewable energy equipment, energy saving equipment and energy conversion equipment is designed, and a mathematical model for optimal scheduling of CIES is established. The model takes into account various optimization objectives, system constraints under different energy demand are considered respectively, and heuristic algorithms are adopted to solve the problem. Finally, the economic of integrated energy load priority (IELP) operation mode is analyzed, and the feasibility and effectiveness of the proposed model is verified. It provides an important theoretical support for participating in energy market transactions considering load priority.

2. CIES framework

![Figure 1. Framework of the CIES.](image)

The community integrated energy system mainly consists of external energy input, distributed units, energy management system, energy coordination device and load. By inputting different kinds of energy sources such as natural gas, electric and illumination wind power, the distributed units sequentially generate and output different kinds and different qualities of energy such as cold, heat, electricity and the like, and then combine energy coordination devices such as pressure transformation, pipeline diversion and the like to meet different levels and different types of user requirements. The structure of the CIES with distributed power sources and multi-type loads established in this paper is shown in "figure 1". The system consists of photovoltaic power generation, wind turbine, cogeneration units and energy management system, which realizes the optimal scheduling of electricity, heat and cold energy. The energy supply side realizes the complementation of energy conversion equipment and distributed power generation equipment with different output characteristics, and the demand side contains translatable electric, heating and cooling loads.

IESP takes into account heat energy and cold energy transactions on the basis of electric energy transactions. Through optimal scheduling of various equipment, IESP outputs various energy such as electricity, heat, and cold, and sells them to end-users, so as to meet diversified demand of users, and makes more profit.

3. Energy supply load priority and satisfaction function

At present, it is difficult to accurately predict the user load. This paper proposes to optimize the multi energy supply through load interval, and adjust the supply priority of cooling, heating and power.
Considering the satisfaction degree of user's energy purchase and the penalty function of energy supply interruption, this paper explores the operation mode of IESP to adjust the priority of energy supply in the load range to maximize profits. The load priority mode of energy supply is based on the user's energy consumption preference. The service provider provides priority to a certain energy within the user's predicted load range to meet the user's maximum demand and energy consumption satisfaction, and cuts other energy within the range to ensure its minimum load demand, so as to achieve the purpose of maximizing profits while satisfying the user's comfort.

Therefore, the load priority in the energy supply side is studied, and the IESP optimize the cooling, heating and power load capacity by priority, and establish the user utility function to indicate the satisfaction degree of the user to purchase the power, heat and cold energy. In addition, the penalty function of energy supply interruption is set to punish the load cut by the service provider, and it is connected with the user utility function to influence the energy supply priority of the energy service provider through the satisfaction of user energy purchase.

4. Mathematical model and operation scheduling model of integrated energy system

4.1. Operation scheduling model based on user satisfaction.
IESP schedules and optimizes the priority output of the equipment on the basis of considering the output on the energy supply side and the load demand on the energy consumption side. The optimization target is the maximum benefit, which can be expressed as follow.

\[
\max P_{IESP} = G_{IESP} - C_{IESP} - S_P + f_{IEC}^T
\]

(1)

\(G_{IESP}\) is the energy supply income to the energy consuming side, \(C_{IESP}\) is the energy supply cost of the service provider, \(S_P\) is the three loads interruption penalty function of cooling, heating and power.

\[
G_{IESP} = \sum_{t=1}^{T} \{ Q^C(t) \cdot R_Q + P^T(t) \cdot R_P + H^T(t) \cdot R_H \}
\]

(2)

\[
C_{IESP} = \sum_{t=1}^{T} \{ C_{gas}(t) + C_{grid}(t) + C_{mt}(t) \}
\]

(3)

\(Q^C(t), P^T(t), H^T(t)\) are the current cooling load, electrical load and thermal load. The energy supply cost includes the cost of purchasing gas from the natural gas company \(C_{gas}(t)\), the cost of purchasing electricity from the power grid \(C_{grid}(t)\) and the cost of operating and maintaining the equipment \(C_{mt}(t)\). When \(C_{grid}(t)\) is greater than 0, it means to purchase electricity from the power grid, otherwise it means to sell electricity online.

\[
S_P = \sum_{s=1}^{T} \{ Q^s_L(t) - Q^s_L(t) \cdot \lambda_Q + H^s_L(t) - H^s_L(t) \cdot \lambda_H + P^s_L(t) - P^s_L(t) \cdot \lambda_P \}
\]

(4)

Where \(\lambda_Q, \lambda_H\) and \(\lambda_P\) are penalty coefficients of CCHP, which are calculated on the basis of customer satisfaction of respective loads. The user satisfaction utility function is usually non-decreasing and convex, with quadratic and logarithmic forms. This paper uses quadratic form to express it:

\[
f_{IEC}^T = \sum_{t=1}^{T} \left\{ v_e P^e(t) - \frac{\alpha_e}{2} (P^e(t))^2 + v_h Q^h(t) - \frac{\alpha_h}{2} (Q^h(t))^2 + v_c H^c(t) - \frac{\alpha_c}{2} (H^c(t))^2 \right\}
\]

(5)

\(v_e, \alpha_e, v_h, \alpha_h, v_c, \alpha_c\) represent preference coefficients for consuming electric energy, heat energy and cold energy, which can reflect the user's preference for energy demand and affect the magnitude of demand.

4.2. System constraint.
The system constraints include the cooling, heating and power load balance constraints and the operation constraints of each equipment in the CCHP micro-network.
Cold load balance constraint, Heat load balance constraint, Electric power balance constraint:

\[ H_{ac}(t) \cdot \text{COP}_{ac} + P_{ec}(t) \cdot \text{COP}_{ec} = Q^l(t) \]  

(6)

\[ H_{ac}(t) \] is the heat power consumed by the absorption chiller in \( t \) period respectively; \( \text{COP}_{ac} \) is the energy efficiency ratio of the absorption chiller, and \( P_{ec}(t) \) is the electric power consumed by the electric chiller during \( t \) period; \( \text{COP}_{ec} \) is the energy efficiency ratio of the electric chiller, where \( Q^l(t) \) is the cooling load demand for \( t \) period.

\[ H_{eh}(t) + H_b(t) + H_{he}(t) - H_{ac}(t) = H^h(t) \]  

(7)

\( H_{eh}(t), H_b(t), H_{he}(t) \) are respectively the heating power output of the electric boiler, the heating power output of the waste heat boiler and the thermal power of the gas boiler in \( t \) period, \( H_{ac}(t) \) is the thermal power consumed by the absorption chiller in \( t \) period, and \( H^h(t) \) is the thermal load demand in \( t \) period.

\[ P_{wt}(t) + P_{pv}(t) + P_{MT}(t) + P_{grid}(t) - P_{ec}(t) - P_{eh}(t) = P^l(t) \]  

(8)

\( P_{wt}(t) \) and \( P_{pv}(t) \) are the output power of wind turbine and photovoltaic respectively in time period \( t \), \( P_{MT}(t) \) and \( P_{grid}(t) \) are respectively the active power emitted by micro gas turbine, the power purchased by power grid in \( t \) period. \( P_{ac}(t) \) and \( P_{eh}(t) \) are the electric power consumed by electric refrigerator and electric boiler respectively in \( t \) period, \( P^l(t) \) is the electric load demand in \( t \) period.

4.3. Solution method.

Equipment operation scheduling is a large-scale nonlinear optimization problem. Therefore, this paper adopts Adaptive-Particle Swarm Optimization (A-PSO) as the optimal solution method, which can reduce the complexity of solution and improve the optimization ability. In the actual solution, the equipment parameters and energy consumption preferences in the period are taken as optimization variables, each variable corresponds to one dimension of the particle, and the fitness is the sum of total revenue minus total cost and penalty function.

5. Case study

Taking a community in Beijing as an example, the IELP cooperative optimization operation strategy proposed in this paper is simulated and analyzed. The output power of wind power and photovoltaic power can be predicted according to historical data. In order to encourage new energy generation and avoid wind and light abandonment, this paper assumes that all new energy generation can be sold. Since the energy trading mode of winter and summer is single and lacks part of the load demand, only the energy conversion process of new energy CCHP system is slightly different, while the load demand in spring and autumn is complete, so this paper only simulates and analyzes the operation and trading process of electricity, heat and cold energy flow in spring and autumn. Equipment capacities and user preference parameters are shown in Table 1.

| Equipment | Power | Equipment | Power | Parameter | value | Parameter | value |
|-----------|-------|-----------|-------|-----------|-------|-----------|-------|
| MT        | 1000  | AC        | 2000  | \( \nu_e \) | 11    | \( \alpha_h \) | 0.015 |
| GB        | 1500  | EC        | 2000  | \( \alpha_e \) | 0.0099 | \( \nu_e \) | 12    |
| WHB       | 1000  | EB        | 2000  | \( \nu_h \) | 12    | \( \alpha_c \) | 0.017 |
In the scheduling optimization model of IELP proposed in this paper, different load priority strategies of service providers can be reflected by adjusting user satisfaction parameters, energy consumption preferences and other parameters.

The forecast interval curves of wind power, photovoltaic power in spring and autumn are shown in the "figure 2(a)". Through Monte Carlo simulation, 100 groups of user load data are tested and optimized, and the average value is taken as the optimization result, as shown in "figure 2(b)".

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**Figure 2. Load forecast and load priority.**

(a) pv\&wt power prediction (b) Load forecasting (c) Electricity priority (d) Heating priority (e) Cooling priority

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**Figure 3. Load priority income comparison.**

In the IELP operation scheme optimization model, the user's energy consumption preference and system income are reflected by adjusting different load priorities. The optimization model is divided into three priority models of electricity priority, heat priority and cold priority, which are optimized by A-PSO algorithm respectively. Finally, the optimal solution of system revenue maximization target under the three load priorities is obtained, as shown in the "figure 2 (c), (d), (e) ". In the case of electricity priority, IESP will give priority to meeting users' electricity demand and cut down the
supply of cold and heat. The same is true for hot and cold priorities. As can be seen from the "figure 3",
under the condition of electricity load priority, the system revenue is 48078.3 yuan and the cost is
39295.4 yuan. Compared with other load priorities, the revenue is the highest, with a net revenue of
8782.9 yuan, followed by a heat load priority of 5173.2 yuan, and a cooling load priority of 3501.3
yuan. Load priority revenue is affected by many factors, including energy output cost, energy price,
user demand and satisfaction, which indicates that users have higher priority on electricity load
demand. It shows that the operation method proposed in this paper can reduce the cost of energy
consumption and improve the economy of energy consumption on the premise of ensuring the comfort
of energy consumption.

6. Conclusion
In this paper, an integrated energy load priority optimal scheduling scheme is proposed for energy
service providers, which considers the user satisfaction and the penalty function of energy supply
interruption. Firstly, the optimal scheduling mathematical model of CIES is established. Then the
various optimization objectives and the constraints of different energy demand are considered, the
heuristic algorithm is used to solve the optimal scheduling, and the economic of operation mode is
analyzed. Finally, the feasibility and effectiveness of the proposed model is verified. The simulation
results show that the operation mode of load priority can optimize the system cost, operation revenue
and customer satisfaction.

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