THERMAL ENERGY CONTROL IN BUILDING ENERGY SYSTEM

by

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There is usually a waste of energy consumption in building systems. To help buildings reduce energy waste, the article established a building-sharing heat and power energy sharing system to achieve optimal energy allocation. Furthermore, the report determined the dual operation strategy model of using heat energy to determine power supply and electricity to determine heat energy. At the same time, we use stochastic programming and multi-objective optimization of the heating model and propose a two-level optimization model solution method based on the Benders decomposition algorithm. At the end of the thesis, the process was applied to actual cases to verify the method's effectiveness.

Key words*: combined cooling, thermal energy storage, stochastic planning building energy system, Benders decomposition algorithm, Pareto optimal solution set, heating and power system*

Introduction

As the global shortage of energy resources and environmental severe pollution have become increasingly prominent in recent years, improving energy efficiency and protecting the environment has attracted widespread attention in the academic community. Moreover, the continuous increase in building energy consumption has exacerbated many environmental, economic, and health issues. To alleviate the environmental pressure and energy crisis, the cogeneration system is widely used to provide energy for buildings. The combined cooling, heating, and power (CCHP) system is a typical energy supply system. Its energy supply equipment is arranged near the end-user in a miniaturized and decentralized form. It provides users with electrical energy, cold energy and thermal energy simultaneously and dramatically improves primary energy utilization. Therefore, studying the optimization of the CCHP system is of great significance for improving building energy utilization and achieving sustainable energy development.

At present, most of the optimization research on the CCHP system focuses on designing and optimizing the combined cooling, heating, and power system of a single building, including deterministic models and stochastic models. For example, in a deterministic environment, some scholars have considered the equipment of the CCHP system. When the capacity is a discrete value, the total cost of a single building is minimized to find the optimal decision-making plan for equipment capacity, the number of equipment, and energy dispatch. Some scholars have analyzed the CCHP system of a single building, consisting of reciprocating internal combustion engines and micro gas turbines. When the fuel cell is used as a power generating set, it has advantages in economic costsaving, energy consumption saving, and environ-

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mental pollution reduction compared with the distribution system that supplies electric energy and heat energy separately. In addition, the energy storage device is introduced into cold and heat power. The cogeneration system can achieve peak shaving and valley filling and further improve energy utilization [1]. Standard energy storage devices include thermal energy storage devices and batteries. In a random environment, most researchers consider random factors such as energy demand and market data (*e.g.*, fuel prices and electricity prices), equipment technology level (*e.g.*, production efficiency) and related policies (*e.g.*, government incentives)*, etc.* When only considering the CCHP system in the operation phase to make energy scheduling plans, some scholars use the cooling, heating, and power of a single building. The co-supply system is the object of optimization. A random mixed-integer programming model is constructed; when considering the design phase (decision equipment capacity and type) and operation phase of the co-supply system, a two-stage stochastic programming method is often used to establish an optimization model. Some scholars obtain optimal equipment configuration and energy scheduling schemes, respectively constructed a two-stage stochastic programming model and a two-stage stochastic robust optimization model and verified the model's effectiveness through numerical experiments. Some scholars considered energy demand and energy prices as uncertain for the design and optimization of the CCHP system of a single building with the introduction of energy storage devices. The scene reduction method is adopted to avoid the high dimensional problem of the two-stage stochastic programming model of the design.

The aforementioned research mainly focuses on the optimization problem when the CCHP system supplies energy for a single building. However, with the promotion of intelligent grids, multiple structures can form a building cluster to share the energy supply system, thereby achieving more significant energy savings. Therefore, it is worthy of in-depth study on optimizing the energy supply system for the sharing and competition relationship between the buildings in the building cluster. For example, without considering the influence of random factors, some scholars have studied the CCHP system as a building composed of two buildings. For the optimal operation problem of energy supply, a mixed-integer programming model was constructed and solved by the simulated annealing method. On this basis, some scholars further studied how to solve the model efficiently and thus proposed an improved multi-objective particle swarm optimization algorithm [2]. Some scholars have established a multi-objective optimization model in the collaborative model to optimize the building-building shared energy supply system in the building cluster to obtain Pareto's optimal design and operation decisions. As a result, some results have been achieved in the optimization research of the building cluster. However, the previous analysis on the optimization of building cluster energy supply system under deterministic environment has performed specific results, few research pieces on the optimization of building cluster CCHP system under random factors. Some scholars have considered the optimization problem of buildings' shared energy supply systems by constructing a two-stage stochastic planning model when the power demand of buildings in the building cluster is random.

This article adopts scenario-based stochastic planning widely used to solve stochastic problems and establishes a stochastic programming model for the energy supply system. In addition, the difficulty of solving the stochastic programming model will become more complicated as the number of scenarios increases and the design is efficient. Therefore, solving algorithms can help improve because of the shortcomings of existing research. This paper conducts modelling and design of solving algorithms. The paper proposes a collaborative decision model to study the inter-buildings in the building cluster the sharing and competition relationship between the CCHP system, thermal energy storage device, and battery form an energy supply system to supply energy for building collections jointly. With multiple goals of minimizing the total cost of each building, a multi-objective stochastic planning model is constructed to effectively solve the random optimization problem of the building energy supply system under the influence of factors. In addition, comprehensive model characteristics and algorithm advantages, the paper use the Benders decomposition algorithm to solve the model to obtain the Pareto curve, which can ensure the quality of the solution and improve the efficiency of the problem.

Questions and definitions

Problem description

This paper studies the energy scheduling optimization problem of buildings sharing CCHP systems, thermal energy storage devices, and batteries in building clusters. The structure of the energy supply system is shown in fig. 1. All buildings in the building cluster can share the energy supply system.

Thermal energy storage devices and batteries have the effect of eliminating peaks and filling valleys, further reducing building energy consumption. The CCHP system includes a power generating units (PGU), boilers (BO), absorption chillers (AC), heat exchangers (HE), thermal energy storage devices (TS), and batteries (BA). The solid lines in fig. 1 represent the flow direction of electrical energy, and the dotted lines represent the flow direction of cold or thermal energy [3]. The electrical energy required by each building can be generated by power generators, batteries, and grid supply. Among them, gas turbines are used as examples of power generating sets, which generate electricity by burning natural gas, and its high temperature waste heat can be recycled.

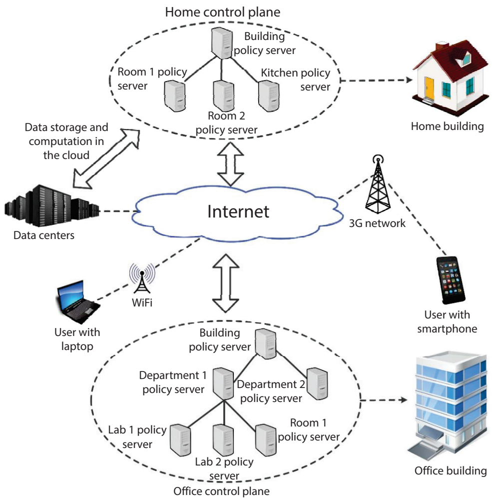

Figure 1. Building cluster energy supply system structure

Symbol definition

In the following study of energy scheduling optimization, the following symbols have been used:

Collections

– t represents the t decision-making cycle, $t = 1, 2,... T$, is the total decision-making cycle,
– i represents the i building, $i = 1, 2, ..., N$, N is the total number of buildings in the building cluster,
– ξ represents the ξ scene, and the corresponding probability is P^{ξ}, $\xi \in \Xi$, Ξ is a set of scenes,
– k_1 represents equipment other than storage, including electric generator sets, boilers, absorption chillers, heat exchangers, $k_1 \in \{\text{PGU, BO, AC, HE}\}$, and
– k_2 represents storage system equipment, including batteries and thermal energy storage devices $k_2 \in \{\text{BA, TS}\}$.

Parameters

– $f_{\text{cost},i}$ represents the total cost of building i,
– $f_{cc,\text{i}}$ represents the equipment investment cost of building i,

– $f_{mc,i}$ represents the equipment maintenance cost of building i,
– $f^{\xi}_{\text{operation},i}$ represents the operating cost of building i in the ξ scenario,
– IE represents, other than energy storage devices, the initial installation cost per 1 kW capacity of the equipment.
– IS represents the initial installation cost per 1 kWh capacity of the energy storage device,
– r represents the annual interest rate,
– n represents the service life of the equipment,
– ME represents the capacity per 1 kW of equipment other than the energy storage device,
– MS represents the maintenance cost per 1 kWh capacity of the energy storage device,
– E represents the cost of purchasing 1 kWh electrical energy from the power grid,
– R_f represents the unit cost of natural gas consumed by the power generating set or boiler,
– R_s represents the price of 1 kWh electrical energy sold to the power grid,
– Egm indicates the upper limit of the purchase of grid power,
– η_{pgu} represents the power generation efficiency coefficient of the power generator set,
– η_p represents the waste heat recovery coefficient of the power generator set,
– η_b represents the thermal energy coefficient of the boiler,
– η_c represents the coefficient of heat energy into cold energy by the absorption chiller,
– η_h represents the efficiency coefficient of the heat exchanger for heating,
– η_{td} represents the coefficient of heat energy released by the thermal energy storage device,
– $utc_{\min}$ represents the lower limit proportional coefficient of the thermal energy storage device of the electric generator set and boiler,
– $utc_{\max}$ represents the storage of the electric generator set and boiler to the thermal energy storage device the upper limit scale factor of thermal energy,
– $utc_{\min}$ represents the lower limit scale factor of thermal energy released by the thermal energy 1,
– M represents a sufficiently large positive number,
– $El^{\xi}_{t,i}$ represents the demand for electrical energy of building i in the decision period t in the ξ scenario,
– $Qc^{\xi}_{t,i}$ represents the demand for cold energy of the building i during the decision period t in the ξ scenario, and
– $Qh^{\xi}_{t,i}$ represents in the ξ scenario, the demand for heat energy of building i during the decision period t.

The two-stage multi-objective stochastic optimization model

Phase 1

For the design and optimization problem of the CCHP system of the building cluster with the introduction of energy storage devices shown in fig. 1, a two-stage stochastic programming model is established. The first stage is the decision-making of the equipment capacity of the energy supply system, and the model at this stage is a multi-objective linear programming model:

$$\min f_{\text{cost},i} = f_{cc,i} + f_{mc,i} + E_{\xi}\left(f^{\xi}_{\text{operation},i}\right) \tag{1}$$

$$f_{cc,i} = \left\{\sum_{k_1} IE_{k_1} cap_{k_1} + \sum_{k_2} IS_{k_2} cap_{k_2}\right\} \times \frac{r(1+r)^n}{(1+r)^n - 1}\frac{T}{8760}\frac{1}{N}, \ \forall k_1, k_2 \tag{2}$$

$$f_{mc,i} = \left\{\sum_{k_1} ME_{k_1} cap_{k_1} + \sum_{k2} MS_{k_1} cap_{k_2}\right\}\frac{T}{8760}\frac{1}{N}, \ \forall k_1, k_2 \tag{3}$$

Equation (1) is the objective function, including three parts: the first stage equipment investment cost, equipment maintenance cost, and the expected value of the second stage objective function in multiple scenarios. The second stage objective function is the first stage decision variable A function of random scenarios [4]. Among them, equipment investment costs and equipment maintenance costs are allocated to: every hour, 365 days a year, 24 hours a day, calculated by eqs. (2) and (3), respectively. The first stage requires to determining the equipment capacity of the energy supply system, with the capacity constraints are:

$$cap_{\mathrm{PGU}}, cap_{\mathrm{BO}}, cap_{\mathrm{AC}}, cap_{\mathrm{HE}}, cap_{\mathrm{BA}}, cap_{\mathrm{TS}} \geq 0 \tag{4}$$

In addition, the upper limit of the value constraint of the equipment capacity of the energy supply system, can be set according to the needs of the decision-maker. This article assumes that the value can be within the range of non-negative numbers.

Phase 2

The second stage is to decide the energy dispatch plan after all the equipment capacity of the energy supply system has been decided, and the random information of energy price or energy demand is known. The goal is the operating cost of the building i in all decision cycles. The model is:

$$\min f_{\mathrm{operation},i}^{\xi} = \sum_{i=1}^{T} \left\{ R_p \left(Egl_{t,i}^{\xi} + Egb_{t,i}^{\xi} \right) + R_f Fp_{t,i}^{\xi} + R_f Fb_{t,i}^{\xi} - R_s Fcg_{t,i}^{\xi} \right\} \tag{5}$$

Equation (5) is the objective function, which includes three parts: the cost of purchasing electric energy from the grid, the cost of fuel consumption, and the income of generating excessive electricity sold to the grid [5]. The relevant equipment operation constraints are as follows.

Electricity purchase constraints

$$\sum_{i=1}^{N} \left(Egl_{t,i}^{\xi} + Epb_{t,i}^{\xi} \right) \leq Egm, \ \forall \xi, t \tag{6}$$

Equation (6) indicates that the electrical energy purchased from the power grid by the building in the building cluster cannot exceed the upper limit of the power supply capacity of the grid in each decision cycle. It is 30 kW.

Energy balance constraints

$$Fp_{t,i}^{\xi} = \eta_{\mathrm{PGU}} \left(Epl_{t,i}^{\xi} + Epb_{t,i}^{\xi} + Ecg_{t,i}^{\xi} \right), \ \forall \xi, t, i \tag{7}$$

$$\sum_{i=1}^{N} \left(Epl_{t,i}^{\xi} + Epb_{t,i}^{\xi} + Eeg_{t,i}^{\xi} \right) \leq cap_{\mathrm{PGU}}, \ \forall \xi, t \tag{8}$$

$$Epl_{t,i}^{\xi} + Egl_{t,i}^{\xi} + Ebl_{t,i}^{\xi} \geq El_{t,i}^{\xi}, \ \forall, t, i \tag{9}$$

Equation (7) indicates that the electric energy generated by the power generator set burning natural gas is used for battery storage, directly supplied to buildings, and sold to the grid. Equation (8) ensures that the electric energy generated by the power generator set cannot exceed its capacity limit. Equation (9) Explain that the sum of the electrical energy directly provided by the power generator set to the building, the electrical energy directly purchased from the grid, and the electrical energy released by the battery to the building must meet the demand electrical energy of the building.

Cold energy/heat energy balance

$$Qfc_{t,i}^{\xi} + Qfh_{t,i}^{\xi} + Qfs_{t,i}^{\xi} \le \eta_p Fp_{t,i}^{\xi} + \eta_b Fb_{t,i}^{\xi}, \ \forall \xi, t, i \tag{10}$$

$$Qcb_{t,i}^{\xi} - \eta_c \left(Qfc_{t,i}^{\xi} + Qsc_{t,i}^{\xi} \right) = 0, \ \forall \xi, t, i \tag{11}$$

$$Qhb_{t,i}^{\xi} - \eta_h \left(Qfh_{t,i}^{\xi} + Qsh_{t,i}^{\xi} \right) = 0, \ \forall \xi, t, i \tag{12}$$

$$\sum_{i=1}^{N} \eta_h Fb_{t,i}^{\xi} \le cap_{\mathrm{BO}}, \ \forall \xi, t \tag{13}$$

$$\sum_{i=1}^{N} Qcb_{t,i}^{\xi} \le cap_{\mathrm{AC}}, \ \forall \xi, t \tag{14}$$

$$\sum_{i=1}^{N} Qhb_{t,i}^{\xi} \le cap_{\mathrm{HE}}, \ \forall \xi, t \tag{15}$$

$$Qcb_{t,i}^{\xi} \ge Qc_{t,i}^{\xi}, \ \forall \xi, t, i \tag{16}$$

$$Qhb_{t,i}^{\xi} \ge Qh_{t,i}^{\xi}, \ \forall, t, i \tag{17}$$

Equation (10) indicates that the sum of the heat energy supplied by the power generator set it boiler to the absorption chiller and heat exchanger. The heat energy stored in the thermal energy storage device does not exceed the high temperature waste heat recovered when the power generator set produces electricity. The boiler burns natural gas [6]. Therefore, the sum of heat energy generated. Equation (11) ensures the energy conservation between the cold energy produced by the absorption refrigerator and the heat energy consumed. Equation (12) ensures the energy conservation between the heat energy generated by the heat exchanger and the heat energy consumed. Equations (13)-(15) represent the capacity constraints of boilers, absorption chillers, and heat exchangers, respectively. Equation (16) shows that the cold energy provided by the energy supply system to the building must meet the requirements of the building. Hence, the demand for cold energy; eq. (17) shows that the heat energy provided by the energy supply system to the building must meet the heat demand of the building.

Model solving

The optimization model of the building energy supply system constructed in this paper is a 0-1 mixed-integer multi-objective stochastic programming model. There is a relationship of mutual influence and mutual restriction between the total cost of multiple buildings. If only one of the goals is considered, then it is impossible to judge the pros and cons of the corresponding decision-making plan. Therefore, we need to find the Pareto optimal solution set in the multi-objective optimization problem. Since the two types of random variables of energy demand and energy price are variables that only take a limited number of discrete values. This stochastic model is transformed into an equivalent deterministic multi-objective programming model [7]. The model can be solved by commercial optimization software. However, as the number of scenarios increases, the solution scale of the mathematical model will increase significantly, and the efficiency of the software solution model will also increase. To improve the efficiency of model solving, it is necessary to select a suitable solution algorithm according to the characteristics of the model in this paper.

Multi-target processing

In the constructed two-stage stochastic planning model, the information of two types of random variables, energy demand, and energy price, are represented by discrete scenarios. The probability of each scenario is p_ξ, the probability is between 0 and 1, and the sum of the probabilities is 1. Through this method, the stochastic programming model can be transformed into an equivalent deterministic model. Therefore, the objective function (1) can be transformed:

$$f_{\mathrm{cos}t,i} = f_{cc,i} + f_{mc,i} + p_\xi \xi^{\xi}_{\mathrm{operation},i} \tag{18}$$

In the first stage, the goal is to minimize the total cost of each building. This paper uses a weighted method to assign weights to the total cost of different buildings. The larger the weight value, the higher the importance. Therefore, the objective function (19) can be transformed in the single objective function:

$$f_{\mathrm{cos}t} = \sum_{i=1}^{N} \omega_i \left(f_{cc,i} + f_{mc,i} + p_\xi f^{\xi}_{\mathrm{operation},i} \right) \tag{19}$$

where ω_i represents the weight of the total cost $f_{\mathrm{cos}t,i}$ of the building i, ω_i, and the sum of the weights is 1. The larger the weight, the higher the importance. If you consider that each building in the building cluster are equally important, you can set $\omega_i = 1/N$.

By transforming multi-objective problems into single-objective problems, the flexibility of decision-making can be enhanced.

Benders decomposition algorithm

Simultaneously, the optimization model of the building energy supply system is a mixed-integer linear programming model. To further improve the solution's efficiency, we use Birge's two-stage Benders decomposition combined with the linear programming relaxation method to solve the MILP model [8]. This article uses a weighted method to verify, and then obtains the mathematical function of the total cost of the building by checking the mathematical equation. The larger the weight value, the higher its importance. Converted into an objective function for checking is shown in eq. (19):

$$0 \le Stc^{\xi}_t,\ Std^{\xi}_t,\ Sbc^{\xi}_t,\ Sbd^{\xi}_t \le 1,\ \forall \xi, t \tag{20}$$

For the optimization problem of the building energy supply system, a two-stage stochastic programming model is constructed. According to the idea of Benders decomposition, the first stage model is regarded as the main problem, and the objective function is changed from eq. (18) to min $\sum_{i=1}^{N} \omega_i (fc_{c,i} + f_{mc,i}) + \theta$. The decision variable constraint is still eq. (4); the second stage model is regarded as a sub-problem, and the objective function is changed from eq. (5) to $\sum_{\xi,i} \omega_i f^{\xi}_{\mathrm{operation},i}$. The value constraints of decision variables are still eqs. (14) and (16).

Case analysis

This paper uses CPLEX software to solve the specific model. The experimental program running configuration environment is a 4-core processor 2.20 GHz Intel-Core-i5, memory 4 G. It used the 24 hours data of a particular day in July as the experimental data source,

$T = 24$, $N = 2$. The demand for electrical and cold energy of the two buildings is shown in figs. 2(a) and 2(b). This shows that the demand for thermal energy is 0. In addition, it is assumed that the demand for electric energy, cold energy, and heat energy of the building is independent of each other in each decision cycle.

This paper considers the energy demand and energy price of buildings as random factors [9]. Energy demand includes electricity demand, cold energy demand, and thermal energy demand. It can be seen that in each decision cycle, the three follow an average distribution $\theta \sim N(\mu, \sigma_2)$. Consequently, and meets $1.96\sigma = 20\%\mu$, energy prices (including electricity prices and fuel prices) change with market changes, assuming that they are uniformly distributed, as shown in tab. 1 – equipment unit capacity cost and equipment unit maintenance cost in tab. 2.

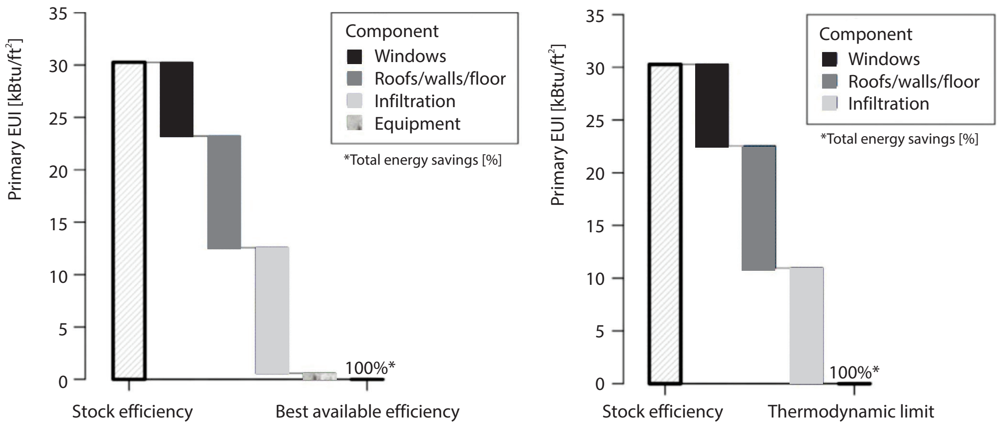

Figure 2. Energy demand of buildings within 24 hours of a particular day in July

Table 1. Uniform distribution of energy prices

Energy price [$]	Evenly distributed
R_p	[0.012, 0.212]
R_f	[0.017, 0.037]

Table 2. Equipment unit capacity cost ($/kW) and maintenance cost ($/kW)

IE_{PGU}	IE_b	IE_{AC}	IE_{HE}	IS_{BA}	IS_{HS}
1000	186	250	300	33	33
ME_{PGU}	ME_b	ME_{AC}	ME_{HE}	MS_{BA}	MS_{HS}
15	3	2	5	1	1

Table 3. Equipment performance parameters

η_{PGU}	η_{P}	η_b	η_c	η_h	η_{td}	η_{bc}	η_{bd}	r [%]	n
6.97	0.51	0.9	0.7	0.85	0.95	0.9	0.9	3	20

Table 4. Comparison of model solution efficiency of Case4 in different scenarios

Problem scale	Constraint variable	7102	14202	42602
	Total number of decision variables	5768	11528	34568
Solving time [s]	Direct solution (CPLEX)	88.62	1208.76	3742.58
	Benders decomposition algorithm solution	5.41	19.87	26.93
Optimal solution [$]	Direct solution (CPLEX)	24.29	24.11	23.17
	Benders decomposition algorithm solution	24.24	24.03	23.09

When the importance of the two buildings is the same (the weight combination is (0.5, 0.5)), when the number of scenes is 5, 10, and 30, respectively, compare the direct use of

CPLEX software and the Benders decomposition algorithm in the model solution time and optimal solution the results are shown in tab. 4. Furthermore, tab. 4 shows that the method proposed in this paper can improve the efficiency of model solving and ensure the quality of the solution. Among them, the scene is randomly generated under the condition of a specific distribution, and Assume that each scenario has an equal probability of occurrence.

Conclusion

This paper considers that under the condition of random energy demand and energy prices, for the design and optimization of the CCHP system of building clusters with energy storage devices, a multi-objective stochastic programming model is established from the perspective of multi-objective and stochastic programming. The article uses a weighted weighting method. Solve the model with Benders decomposition algorithm, and analyze the model's effectiveness and algorithm through random generation scenarios. This article assumes that the random factors are independent of each other. In the follow-up research, we can discuss the correlation of random factors – the optimization problem of the building energy supply system and the design of a more efficient solution algorithm.

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