Multi-objective Optimization Model of Source-Load-Storage Synergetic Dispatch for Building Energy System Based on TOU Price Demand Response

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***Abstract*–The optimized operation of a building energy management system (BEMS) is of great significance to its operation security, economy and efficiency. This paper proposes a multi-objective optimization model for a BEMS under time-of-use (TOU) price based demand response (DR), which integrates building integrated photovoltaic (BIPV) with other generations to optimize the system economy and occupants' comfort by the synergetic dispatch of source-load-storage. The comfort objective established by modelling the indoor environment contains three aspects: visual comfort, thermal comfort, and indoor air quality comfort. With the consideration of controllable loads that could participate in DR programs, the balances among different energy styles, electric, thermal and cooling loads are guaranteed during the optimized operation. YALMIP toolbox in MATLAB was applied to solve the proposed algorithm. Finally, a case study was conducted to validate the effectiveness and adaptability of the proposed model.**

***Index Terms*–Building energy management system; demand response; indoor environmental modelling; multi-objective optimization; optimized dispatch; YALMIP toolbox**

I. NOMENCLATURE

t	Time interval
n	The number of lights
ϕ	Each light source flux (lm)
U	Utilization factor of the light source
M	Maintenance factor of the light source
A	Illuminated room area (m^2)
E_{SET}	Standard illuminance (lux)
R_{eq}	Room equivalent thermal (℃/W)
M_{air}	Indoor air quality (kg)
C_p	Air specific heat capacity(J/(kg·℃))
T_{SET}	Standard temperature (℃)
L	Amount of fresh air (m^3/s)
N_w	Outdoor CO_2 concentration (ppm)
V	Volume of the room (m^3)
v_{co_2}	Indoor CO_2 generation at time t (m^3)
R	Fresh air cooling load (kW)
ρ	Air density (kg/m^3)
h_w	Outdoor air enthalpy (kJ/kg)
h_n	Indoor air enthalpy (kJ/kg)
d	Moisture content in the air (g/kg)
N_{SET}	Standard CO_2 concentration (ppm)
η_{CHP}	Efficiency of MT (%)
η_l	Heat loss rate of CHP (%)
LHV_{NG}	Low calorific value of natural gas (kWh/m^3)
P_{NG}	Unit price of natural gas (¥)
R_{GB}	Rated heat of boiler (kW)
η_{GB}	Thermal Efficiency of GB (%)
η_{ch}	Charge efficiency (%)
η_{dis}	Discharge efficiency (%)
C_{mi}	Unit operation costs (¥)
C_{SC}^U	Start-up costs of CHP (¥)
$C_b(t)$	Electricity sale price at time t (¥)
$C_s(t)$	Electricity purchase price at time t (¥)
α_j	Conversion factor of pollutant j (¥/kg)
$\beta_{i,j}$	Emission factor of generation i for pollutant j (kg/kW)
t_d	Starting time of deferrable loads (h)
$x_{t\to t'}$	Amount of deferrable load shift from time t to t' (kW)
x_t	Amount of deferrable load at time t before optimization (kW)
$E(t)$	Indoor illumination at time t (lux)
$T_{room}(t)$	Indoor temperature at time t (℃)
$T_{out}(t)$	Outdoor temperature at time t (℃)
$Q(t)$	Heat transferred from indoor at time t (J)
$N(t)$	Indoor CO_2 concentration at time t (ppm)
$P_E(t)$	Lighting power at time t (kW)
$P_L(t)$	Total electrical load power at time t (kW)
$P_{CHP}(t)$	Electric power output of CHP at time t (kW)
$P_{PV}(t)$	BIPV power output at time t (kW)
$P_{EX}(t)$	Interactive power with grid at time t (kW)

$P_{EES}(t)$	Electric power output of EES at time t (kW)
$E_{EES}(t)$	State of charge for EES at time t (kW)
$Q_L(t)$	Total heat load power at time t (kW)
$Q_{CHP}(t)$	Heat power output of CHP at time t (kW)
$Q_{GB}(t)$	Heat power output of GB at time t (kW)
$Q_{TES}(t)$	Heat power output of TES at time t (kW)
$H_{TES}(t)$	Capacity of TES at time t (kW)
$R_L(t)$	Total cooling load power at time t (kW)
$R_{AR}(t)$	AR cooling load power at time t (kW)
$R_{ECR}(t)$	ECR cooling load power at time t (kW)
$V_{CHP}(t)$	Natural gas consumption of CHP at time t (m^3)
$V_{GB}(t)$	Natural gas consumption of GB at time t (m^3)

II. INTRODUCTION

With the increasing urbanization in recent years, a great deal of buildings' emergence has resulted in a large energy consumption proportion of buildings [1]. Consequently, building energy saving and efficiency improvement are imminent, especially in the situations of energy crisis and environmental pollution [2]. The main function of building energy management system (BEMS) is to manage and control the energy flow in the building through different kinds of information so as to ensure the operation safety, reliability and economy [3]. For a complex system such as building energy system (BES), structure, service and management are closely connected and must be considered together simultaneously [4]. The building integrated photovoltaic (BIPV) is very popular in modern building for its eco-friendly and economic characteristics [5].

In order to improve the efficiency of BES, the optimized dispatch of different generations or loads is a very important issue during the operation, which is influenced by many factors. The output of photovoltaic (PV) is random because of the variation of weather conditions [6], which affect the dispatch accuracy greatly. As a result, to improve the predicted precision of PV output is an important premise for the follow-up work [7]. And as the development of demand response (DR), the demand side has to be considered to improve the system reliability [8]-[9]. In addition, energy storage also plays a significant role in smart building's operation optimization [10]. Researchers around the world have devoted much effort to study the optimized operation of BES and gained a lot of achievements [11]-[13]. A distributed management method for BES was proposed using multi-agent system to improve the energy efficiency and reducing energy costs [14]. Andrea Staino etc. presented a cooperative optimization approach for a group of buildings to realize economic operation and load reduction [15].

The overall optimization objective of BEMS is to meet occupants' comfort while reduce energy consumption and improve economy for the whole system. A model of BEMS which considered the occupants' comfort and the energy consumption was raised in [16]. Reference [17] integrated the plug-in hybrid electric vehicle (PHEV) into energy and comfort management in a smart building environment. An intelligent building fuzzy control theory was proposed in [18], which was used to calculate the required energy consumption used to achieve the setting comfort level. All the studies achieved good results in BES application.

BES is a highly complex system and the optimal state of the overall system must take all kinds of power sources, loads and energy storage devices into account. In addition, the uncertainties of BIPV's output and load fluctuation directly affect the economic operation of BES. But the existing researches usually focus on the single optimization of power supplies or loads, and the comprehensive optimization combining sources, loads and storages together are relatively rare. On the other hand, the model of each unit was relatively simple. And different types of load that could take part in DR programs such as deferrable load and controllable load were not dispatched concertedly.

In this paper, the energy economy and occupants' comfort level were considered at the same time for a large commercial building. Based on the classified model of different kinds of loads in the building, DR was carried out effectively in the conditions of time-of-use (TOU) price. The model of indoor environment was established by the construction of visual comfort, thermal comfort and indoor air quality comfort which are considered as the three most important factors for building indoor environment [19]. Based on the prediction of BIPV's output, non-controllable loads and outdoor temperature, this paper established a multi-objective optimization model with relevant constrains to improve the occupants' comfort and economy through the coordinated optimization among sources, storage devices and loads. YALMIP toolbox in MATLAB was chosen to solve the model for its convenience and quickness. Finally, an example was conducted to verify the effectiveness of this method.

The remainder of this paper is organized as follows. In Section III, the studied BES was described in detail. In Section IV, the models of indoor environment parameters and comfort level were presented. Then Section V proposed the optimization model, including the optimization objectives and the constraints. Section VI provided a simulation analysis and a conclusion was given in Section VII.

III. THE BUILDING ENERGY SYSTEM

The BES considered in this paper included BIPV, utility grid, controllable generations such as combined heat and power (CHP) system and gas boiler (GB), electricity energy storage (EES) device, thermal energy storage (TES) device and loads which consisted of electrical load (EL), hot water load (HL) and cooling load (CL). In this paper, a typical summer day was analyzed during the optimization and the system CL was composed by indoor cooling load (ICL) and fresh air cooling load

(FACL) which were supplied by electric compression refrigeration (ECR) combined with absorption refrigeration (AR). The structure of the BES in this paper is shown in Fig. 1.

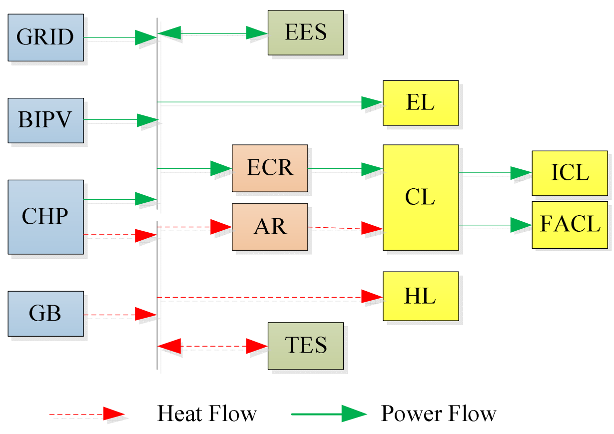

Fig. 1. The structure of the BES

A. Building Integrated Photovoltaic system (BIPV)

BIPV is a new concept for solar power application and an advanced form of photovoltaic power generation integrated in building [20]. It has higher requirements for PV modules which not only need to meet the functional requirements of photovoltaic power generation but also need to take the basic functional requirements of the building into account.

The power output of photovoltaic system changes with the seasons, weather, solar radiation, temperature and other factors, which is very unstable and difficult to adjust according to actual demands [21]. Thus, forecasting the output power of photovoltaic generation system is one of the foundations for the optimization of building energy management.

B. The Model of Controllable Generations and Storage Devices

CHP system, which use micro turbine (MT) as the motive device, could provide electrical power and utilize waste heat to meet the heating load or cooling load demand of building system at the same time.

The CHP system model can be expressed as [22]:

$$Q_{CHP}(t) = \frac{P_{CHP}(t)(1-\eta_{CHP}-\eta_l)}{\eta_{CHP}} \tag{1}$$

$$V_{CHP}(t) = \frac{P_{CHP}(t)\Delta t}{\eta_{CHP} \times LHV_{NG}} \tag{2}$$

$$C_F = \sum_{t=1}^{24} P_{NG} \times V_{CHP}(t) = \sum_{t=1}^{24} P_{NG} \times \frac{P_{CHP}(t)\Delta t}{\eta_{CHP} \times LHV_{NG}} \tag{3}$$

GB coordinates the CHP system to meet the thermal load demand of the system and the mathematical model can be expressed as [17]:

$$Q_{GB} = R_{GB} \times \eta_{GB} \tag{4}$$

$$V_{GB}(t) = \frac{Q_{GB}(t)\Delta t}{\eta_{GB} \times LHV_{NG}} \tag{5}$$

$$C_F = \sum_{t=1}^{24} P_{NG} \times V_{GB}(t) = \sum_{t=1}^{24} P_{NG} \times \frac{Q_{GB}(t)\Delta t}{\eta_{GB} LHV_{NG}} \tag{6}$$

Energy storage systems which included EES and TES play a dual role of power and load, which could coordinate the imbalance between the power source and load within the system, improve the system reliability and economy and play a part in load shifting at the same time.

The model of EES and TES can be expressed as [23]:

$$E_{EES}(t) = E_{EES}(t-1) - \frac{P_{EES\_dis}\Delta t}{\eta_{dis}} + P_{EES\_ch}\Delta t \eta_{ch} \tag{7}$$

$$H_{TES}(t) = H_{TES}(t-1) - \frac{Q_{TES\_dis}\Delta t}{\eta_{dis}} + Q_{TES\_ch}\Delta t \eta_{ch} \tag{8}$$

C. Load Model Description

According to the characteristics, the loads can be divided into non-controllable loads and the loads that could participate in DR. The latter can be further split into controllable loads and deferrable loads. This paper concentrated on optimizing the loads that can participate in DR.

Controllable loads such as office lights and air conditioning, whose energy consumption accounts for about 70% of building's total consumption.

Deferrable loads mainly refer to the loads whose operation time could be adjusted, such as the washing machines and other electrical equipment in building. By altering the starting time of deferrable loads in appropriate period, the overall economy could be improved without changing their basic electric characteristics.

IV. Indoor Environment Modelling

In order to understand the optimization procedure preferably, a room model was shown in Fig. 2 and assuming that all the rooms were the same in this simulation.

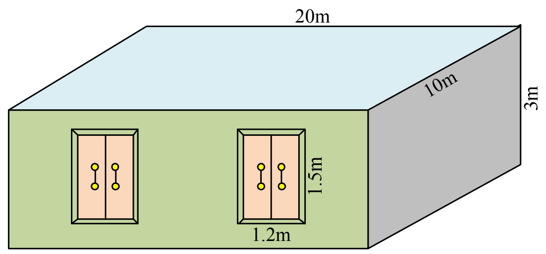

Fig. 2. Schematic view of room in BES

The room is an environment with a rectangular plan whose length is 20m, the depth is 10m, and the height is 3m. There are four windows in the room whose length is 1.2m and height is 1.5m.

Visual comfort, thermal comfort and indoor air quality comfort are the three basic factors that determine the environmental conditions in a building. Illumination level can be taken as the index for visual comfort. Thermal comfort in a room is determined by the indoor temperature. And CO_2 concentration is an index for evaluating the indoor air quality which can be improved by the ventilation system generally [24].

A. Visual Comfort

For the lighting equipment whose luminance could be adjusted, its power can be continuously changed within a certain range, namely indoor illumination varies with the power change of lighting devices. The indoor illumination index can be expressed as:

$$E = \frac{nP_E \phi UM}{A} \tag{9}$$

The value of n, ϕ, U and M are taken 20, 5000 lm, 0.8 and 0.8 in the optimization model of this paper, respectively. The illuminated room area is 200 m^2.

Visual comfort index is represented by indoor illumination which changes within the acceptable range set by users:

$$D_1(t) = 1 - \left(\frac{E(t) - E_{SET}}{E_{SET}} \right)^2 \tag{10}$$

where $D_1(t)$ represents the visual comfort at time t.

B. Indoor Air Quality Comfort

Air conditioning model is regarded as a "black box" that the internal structure is unknown when considering the energy consumption. The mathematical relationship among indoor temperature, outdoor temperature and the energy consumption of air conditioning is shown as follows:

$$T_{room}(t) = T_{room}(t-1) + \frac{\dfrac{T_{out}(t) - T_{room}(t-1)}{R_{eq}} - Q(t)}{M_{air} C_p} \tag{11}$$

The house wall is equivalent to building brick whose thickness is 240 mm and the windows are equivalent to glass whose thickness is 10 mm. The thermal conductivity of house wall and windows are 0.69 W/(m·K) and 1.09 W/(m·K), respectively. And R_{eq} is calculated by:

$$R_{eq} = \frac{R_{wall} R_{window}}{R_{wall} + R_{window}} \tag{12}$$

where M_{air} and C_p are respectively 723 kg and 1005.4 J/(kg·℃).

To maintain a good indoor air quality, the indoor CO_2 concentration must be remained stable and the ventilation system must provide a certain amount of fresh air into the room. Mathematical relationship between indoor CO_2 concentration and the amount of fresh air can be expressed as [25]:

$$N(t) = N(t-1) + \frac{L \times N_w - L \times N(t-1) + v_{co_2}}{V} \tag{13}$$

And the model of fresh air cooling load is:

$$R = \rho \times L \times (h_w - h_n) \tag{14}$$

h_w and h_n can be calculated by:

$$h(t) = 1.01 \times T(t) + \frac{d(t)}{1000} \times (2500 + 1.84 \times T(t)) \tag{15}$$

The value of v_{CO2} is 0.000056m^3/s and ρ is 1.2 kg/m^3. The volume of the house is 600 m^3.

Indoor air quality comfort index is represented by indoor CO_2 concentration and it changes within the acceptable range that was set by users:

$$D_2(t) = 1 - \left(\frac{N(t) - N_{SET}}{N_{SET}} \right)^2 \tag{16}$$

where $D_2(t)$ represents the indoor air quality comfort at time t.

C. Thermal Comfort

The thermal comfort index is represented by indoor temperature and it changes within the acceptable range that was set by users:

$$D_3(t) = 1 - \left(\frac{T_{room}(t) - T_{SET}}{T_{SET}} \right)^2 \tag{17}$$

where $D_3(t)$ represents the thermal comfort at time t.

V. OPTIMIZATION MODEL

The operation objective of the BEMS is to maximize the energy economy while the occupants' comfort is guaranteed. Based on the prediction of BIPV's output, non-controllable loads and outdoor temperature, BEMS optimizes the operation of all components of the system in presence of different physical constraints. In this paper, the optimized results contained power output of uncontrollable generations, power exchanged with utility grid, storage charge/discharge curve, controllable load power curve, deferrable load power curve and indoor environment parameters. The whole optimization structure chart is shown in Fig. 3.

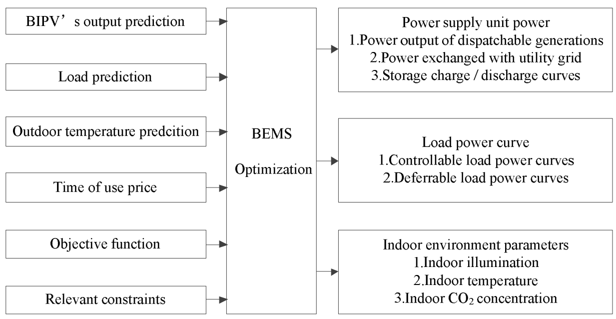

Fig. 3. Optimization structure chart for BEMS

A. Economic Optimization Objective

The economic objective is to minimize the total daily cost, which includes: the fuel cost of CHP and GB; the operation and maintenance cost of BIPV, CHP and GB; the controllable unit start-up cost of CHP and GB; the cost of electricity purchased from the grid and the revenue from electricity sold to the grid; the environmental conversion cost of utility grid, CHP and GB. The total cost can be calculated as follow:

$$C = \sum_{t=1}^{24} [C_F(t) + C_{OM}(t) + C_{SC}(t) + C_{EX}(t) + C_{EN}(t)] \tag{18}$$

where C represents the total cost in an optimization cycle. $C_F(t)$, $C_{OM}(t)$, $C_{SC}(t)$, $C_{EX}(t)$ and $C_{EN}(t)$ are respectively fuel cost, operation and maintenance cost, controllable unit start-up cost, grid interactive power cost (income) and environmental conversion cost.

1) Fuel cost of CHP and GB can be expressed as:

$$C_F(t) = P_{NG} \times \frac{P_{CHP}(t)\Delta t}{\eta_{CHP} \times LHV_{NG}} \tag{19}$$

$$C_F(t) = P_{NG} \times \frac{Q_{GB}(t)\Delta t}{\eta_{GB} LHV_{NG}} \tag{20}$$

The value of LHV_{NG} is 9.78 kW·h/m^3 and P_{NG} is 2.2 yuan/ m^3 .

2) Operation and maintenance cost includes the operating and management cost of BIPV, CHP and GB:

$$C_{OM}(t) = \sum_{i=1}^{3} P_i(t) C_{mi} \tag{21}$$

3) $U(t)$=1 when CHP or GB is under working condition, otherwise $U(t)$=0. The start-up cost of controllable unit can be expressed as:

$$C_{SC}(t) = \max\{0, U(t) - U(t-1)\} C_{SC}^{U} \tag{22}$$

4) Grid interactive power cost can be expressed by electricity sale price and purchase price:

$$C_{EX}(t) = \frac{C_b(t) + C_s(t)}{2} P_{EX}(t) + \frac{C_b(t) + C_s(t)}{2} \left| P_{EX}(t) \right| \tag{23}$$

5) Environmental conversion cost includes the cost of utility grid, CHP, GB and the main pollutants required conversion include CO_2, SO_2 and NO_X. The conversion factors and emission factors are shown in Table I.

$$C_{EN}(t) = \sum_{i=1}^{3} \sum_{j=1}^{3} \alpha_j \cdot \beta_{i,j} \cdot P_i(t) \tag{24}$$

TABLE I

CONVERSION AND EMISSION FACTORS FOR POLLUTANTS

Type	Conversion Factors /(¥/kg)	Emission Factors CHP /(kg/kW)	GRID /(kg/kW)	GB /(kg/kW)
CO_2	6.65	0.1995*10^{-3}	0.2469*10^{-3}	0.0997*10^{-3}
SO_2	2.375	1*10^{-9}	0.5*10^{-6}	0.556*10^{-9}
NO_X	2.12	0.55*10^{-9}	0.444*10^{-6}	0.278*10^{-9}

B. Comfort Optimization Objective

The occupants' comfort is determined by three basic comfort factors as shown in Section IV. The general control goal is to maintain the comfort value within a reasonable range in different conditions and the total comfort level can be expressed as follow:

$$D = \sum_{t=1}^{24} [\alpha D_1(t) + \beta D_2(t) + \gamma D_3(t)] \tag{25}$$

where D represents the total comfort in an optimization cycle, among which α, β, γ are set by the users [26] according to their own preferences and satisfy $\alpha+\beta+\gamma=1$. It is taken $\alpha=\beta=\gamma=1/3$ in this simulation of the paper.

C. Overall Optimization Objective

In multi-objective optimization problems, the objectives to be optimized are usually in conflict with each other. In this paper, the weighted aggregation method is utilized to transfer a multi-objective optimization into a single objective optimization. The overall optimization objective is expressed as:

$$\min F = \mu C + \lambda(1-\mu)\frac{1}{D} \tag{26}$$

where μ is the weight between economy and comfort level which is set by the users according to their actual demand and λ is used to balance the difference between the two different dimensions.

D. Operation Constraints

1) Power Balance

In each dispatch interval, the total energy consumption including electrical, heating and cooling load should be equal to the energy supplied by the power sources:

$$P_L(t) = P_{PV}(t) + P_{CHP}(t) + P_{EES}(t) + P_{EX}(t) \tag{27}$$

$$Q_L(t) = Q_{CHP}(t) + Q_{GB}(t) + Q_{TES}(t) \tag{28}$$

$$R_L(t) = R_{AR}(t) + R_{ECR}(t) \tag{29}$$

2) Power Output Constraints

The output of each equipment should not exceed the power or capacity range.

$$P_{CHP\min} \le P_{CHP}(t) \le P_{CHP\max} \tag{30}$$

$$P_{EX\min} \le P_{EX}(t) \le P_{EX\max} \tag{31}$$

$$P_{EES\min} \le P_{EES}(t) \le P_{EES\max} \tag{32}$$

$$Q_{TES\min} \le Q_{TES}(t) \le Q_{TES\max} \tag{33}$$

$$Q_{GB\min} \le Q_{GB}(t) \le Q_{GB\max} \tag{34}$$

3) Capacity Constraints

Energy stored in the storage devices at time t is equal to the amount stored at time t-1 minus the energy discharged or plus the energy charged. The stored energy cannot exceed the designed range:

$$E_{EES\min} \le E_{EES}(t) \le E_{EES\max} \tag{35}$$

$$H_{TES\min} \le H_{TES}(t) \le H_{TES\max} \tag{36}$$

4) Starting Time and Deferrable Amount Constraints

The starting time of deferrable loads must change within the time interval that the users defined [27]:

$$t_{d\min} \le t_d \le t_{d\max} \tag{37}$$

$$x_{t \to t'} \ge 0 \tag{38}$$

$$\sum_{t'=1}^{T} x_{t \to t'} = x_t \tag{39}$$

5) Indoor Environment Parameters Constraints

Indoor environment parameters cannot exceed the defined range set by the occupants during the optimization process:

$$E_{\min} \le E(t) \le E_{\max} \tag{40}$$

$$T_{room\min} \le T_{room}(t) \le T_{room\max} \tag{41}$$

$$N_{\min} \le N(t) \le N_{\max} \tag{42}$$

VI. SIMULATION ANALYSIS

The BEMS is constituted by the following components: the power sources include BIPV, the utility grid, controllable generations such as CHP, GB, EES and TES device; controllable loads include lighting and air conditioning, while the deferrable loads contain washing machine, disinfection cabinet and dishwasher [28].

TOU price has been considered within the optimization strategy. System operating parameters are shown in Table II and parameters of all kinds of deferrable loads are shown in Table III.

TABLE II

SYSTEM OPERATING PARAMETERS

Power Supply	Output Power Limit/kW		Fuel Cost /(¥/kW)	Operation and Management Cost/(¥/kW)	Start-up Cost/¥
	Lower	Upper			
BIPV	0	70	—	0.0096	—
CHP	0	65	0.75	0.0401	3
GB	0	100	0.25	0.0102	1
EES	-3	3	—	—	—
TES	-5	5	—	—	—

TABLE III

DEFERRABLE LOADS PARAMETERS

Type	Power(kW)	Earliest starting time(h)	Latest starting time(h)	Duration (h)
Washing machine	0.4 0.25	8:00	16:00	2
Disinfection cabinet	0.7	1:00	24:00	1
Dishwasher	2 1.5 1.2	7:00	19:00	3

The initial values of the indoor environment, standard setting values and user's allowable variation range are shown in Table IV. TOU price and predictive values are shown in Fig. 4.

TABLE IV

INDOOR ENVIRONMENTAL PARAMETERS

Parameters	Initial	Set	Maximum	Minimum
Illuminance/lux	320	320	320	290
Temperature/°C	25	25	27	25
CO_2/ppm	800	800	1000	800

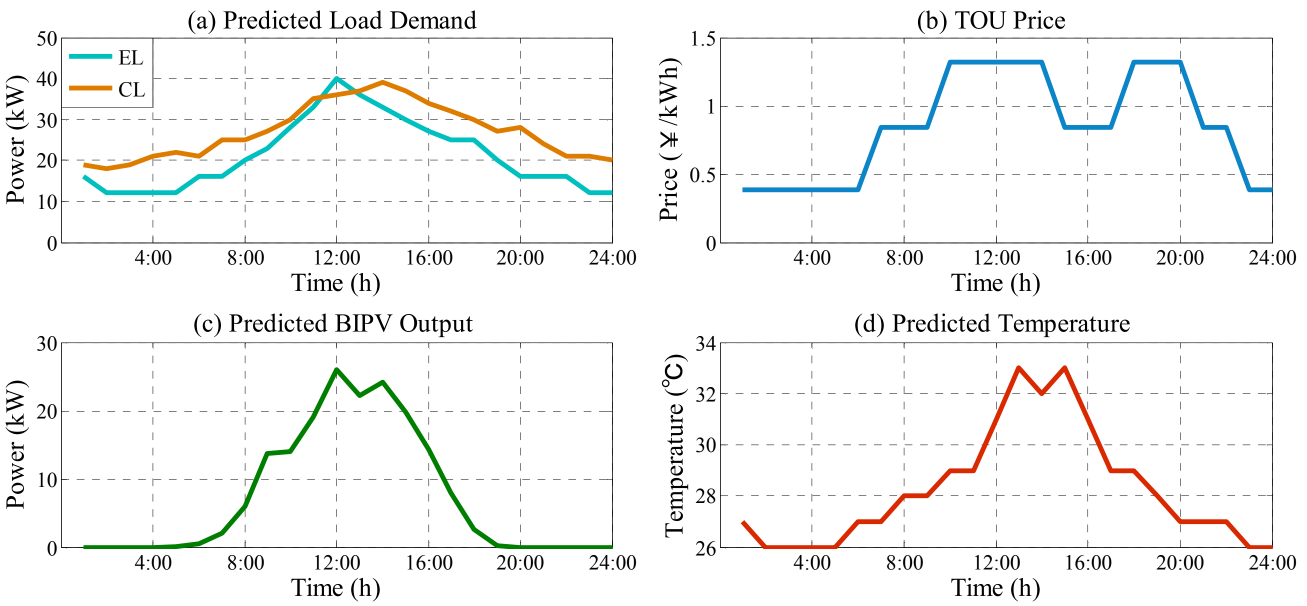

Fig. 4. The TOU price and predictive values

In the optimization model established in this paper, the objective function can be expressed by the decision variables:

$$\min F = g(P_{CHP}, P_{GB}, P_{PV}, P_{EX}, E, T_{room}, N) \quad (43)$$

The optimization model can be solved by the YALMIP toolbox in MTALAB and the flow chart is shown in Fig. 5. The optimization process can be represented as:

(1) Get the predicted values including BIPV's output, uncontrollable load power and outdoor temperature.

(2) Run the YALMIP toolbox according to the objective function and the constraints.

(3) Generate the optimization program such as the power outputs of uncontrollable generations, power exchanged with utility grid, storage charge/discharge, controllable load power, deferrable load power and indoor environment parameters. Then show them in figures.

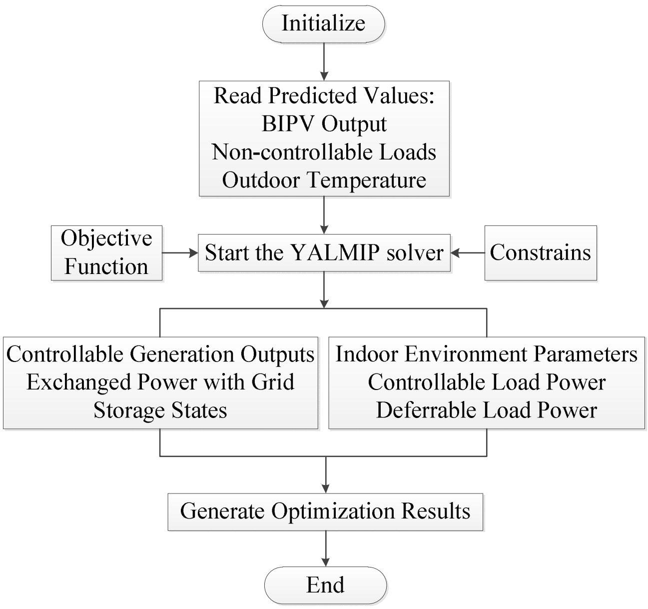

Fig. 5. Flow chart of optimization process

The optimization results for electric, heating, cooling loads and storage device are shown in Fig. 6-9. As we can see in Fig. 6, when the TOU price was low, the electric load was mainly supplied by the utility grid, and the CHP system ran on full power state when the TOU price was expensive. The optimization results are consistent to the objective which aims to maximize the system economy. In Fig. 8, the cooling load was mainly satisfied by AR and the shortfall of cooling load was met by ECR. AR could make use of the waste heat produced by CHP and has a series of advantages such as low cost and high energy efficiency, which is in line with the economic optimization goal. Consequently, AR was prior to be used in the operation process.

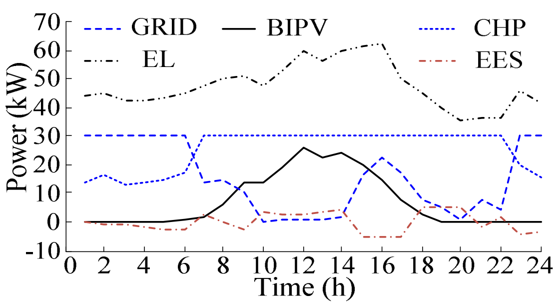

Fig.6. The optimization results for electric load balance

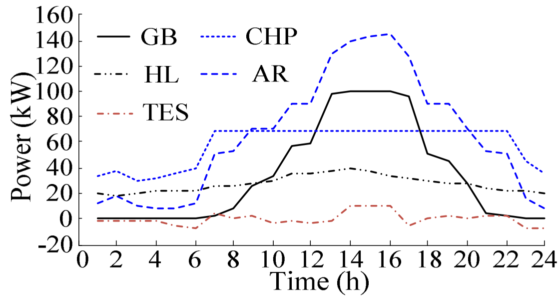

Fig. 7. The optimization results for heating load balance

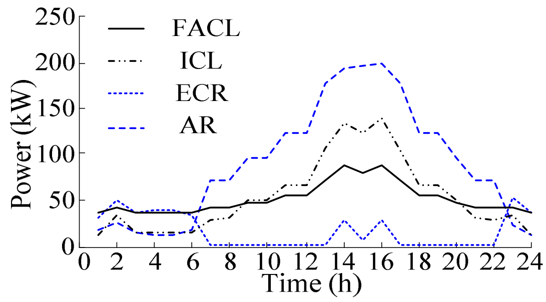

Fig. 8. The optimization results for cooling load balance

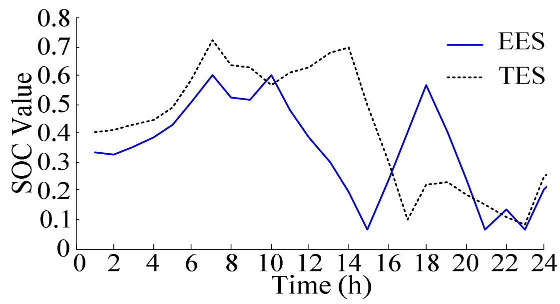

Fig. 9. The optimization results for storage device state

The optimization results for indoor environmental parameters are shown in Fig. 10-12, while the optimization results for deferrable loads are shown in Fig. 13.

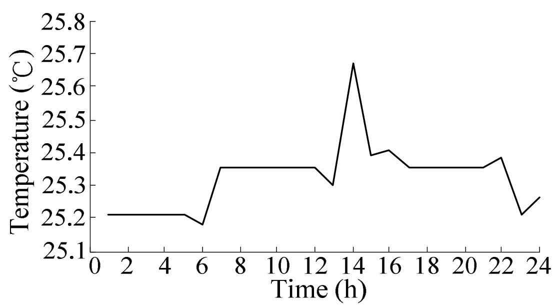

Fig. 10. The optimization results for indoor temperature parameters

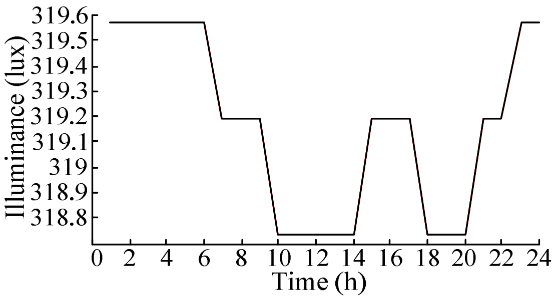

Fig. 11. The optimization results for indoor visual parameters

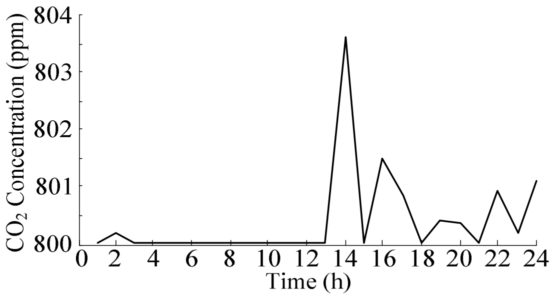

Fig. 12. The optimization results for indoor air quality parameters

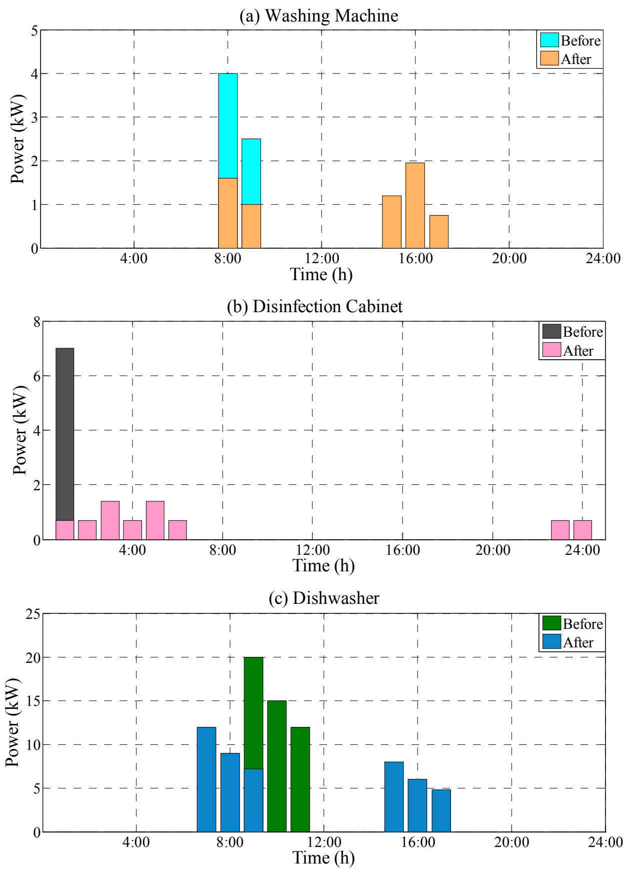

Fig. 13. The optimization results for deferrable loads

From the results, it could be found that all the indoor environment indexes are limited in setting range, guaranteeing the comfort feel for occupants. And the deferrable loads realize the time translation according to the dispatch scheme, aiming to achieve higher economic benefits without affecting people's life quality. To be specific, in order to ensure the system economy during peak price periods, optimization results of controllable load reduced significantly [29], which resulted in a change of indoor environment parameters and the comfort level reduced slightly within an acceptable range.

When the electricity price was low, indoor illuminance raised, temperature and CO_2 concentration values were relatively low, a relatively good indoor environmental comfort could be maintained. The reduction of controllable loads plays an important role in load shifting and improving the system economy, which has great significance for the security and stability of the utility grid [30].

Changing the starting time of deferrable loads within the range set by the users could avoid the power growth on peak period and improve the economy of the system without changing its basic electrical properties.

The occupants determine the weight between economy and comfort based on the actual needs to improve overall system economy and ensure the indoor environment within an acceptable range. The optimization results reflect the balance between system economy and comfort. As we can see in Table V, compared with the value without optimization, the total cost decreased 4.88% while the comfort index declined only 0.15% after optimization.

TABLE V

THE RESULTS BEFORE AND AFTER OPTIMIZATION

Results	Before	After	Change/%
Fuel cost	905.45	861.31	-4.87
Operation and maintenance cost (¥)	35.03	34.2	-2.37
Environmental conversion cost (¥)	2	1.94	-3
Total cost (¥)	943.49	897.45	-4.88
Comfort level	1	0.9985	-0.15

Through the optimization, the proposed method achieves the collaborative optimization of all kinds of power sources, loads and energy storage systems, maintaining the occupants' comfort and enhancing the economy of the system at the same time.

VII. Conclusion

This paper presented an optimization model for intelligent BEMS based on the prediction of BIPV's output, in which the non-controllable load, outdoor temperature and overall economy of the building system, and also occupants' indoor environmental comforts were considered. The collaborative operation of power supplies, loads and storage devices was implemented by the optimization of controllable generations, DR loads and storage devices. The simulation showed that the occupants could set the weight according to the actual demand and improve the economy without affecting their comfort by a combined optimization objective of economy and comfort.

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