Performance Analysis and Comparison on Energy Storage Devices for Smart Building Energy Management

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***Abstract*—A smart building energy system usually contains multiple energy sources such as power grids, autonomous generators, renewable resources, storage devices, and schedulable loads. Storage devices such as batteries, ice/heat storage units, and water tanks play an important role in reducing energy cost in building energy systems since they can help sufficiently utilize renewable energy resources and time-of-use electricity prices. It is important to plan, schedule, and coordinate all the storage devices together with schedulable loads in a building facilitated by microgrid technology. To consider the above problem with uncertainties in solar radiation and demand profiles, a stochastic optimization problem is formulated and solved by the scenario tree method. The best combination and the optimal capacities of storage devices for specific building energy systems are then determined. Furthermore, the optimal operating strategy of building energy systems can be obtained. The performance analysis on the storage devices is conducted and the numerical results show that thermal storage devices (e.g., ice storage units, water tanks) are good for saving energy costs but batteries may not be economical due to their high investment cost and short lifetime. It is also observed that the aforementioned uncertainties have an impact on selecting which type and capacity of storage device should be used.**

***Index Terms*—Building energy saving, mixed integer programming, optimal capacities and types, storage devices.**

I. NOMENCLATURE

a_b	NIT price of battery (RMB/kWh).
a_h	Unit price of heat storage unit (RMB/kWh).
a_q	Unit price of ice storage unit (RMB/kWh).
a_w	Unit price of water tank $(\mathrm{RMB/m^3})$.
b_l	Upper lifetime of battery converted to scheduling horizon.
c_b	Penalty due to using battery during scheduling horizon (RMB).
$\overline{c_b}$	Penalty cost when the utilization time of battery exceed b_l (RMB).
c_{bic}	Investment cost of battery (RMB).
c_{hic}	Investment cost of heat storage unit (RMB).
c_{qic}	Investment cost of ice storage unit (RMB).
c_{wic}	Investment cost of water tank (RMB).
$c_p^d(k)$	Buying price of electricity during k $(\mathrm{RMB/kWh})$.
$c_p^u(k)$	Selling price of electricity during k $(\mathrm{RMB/kWh})$.
$C_k^p(\cdot)$	Total cost of electricity during k (RMB).
$c_n(k)$	Price of natural gas during k $(\mathrm{RMB/m^3})$.
$C_k^n(\cdot)$	Total cost of natural gas during k (RMB).
$cop(k)$	Coefficient of performance in refrigeration mode.
$cop_h(k)$	Coefficient of performance in heating mode.
$copi(k)$	Coefficient of performance in ice-making mode.
$e_{ae}(k)$	Electrical consumption by auxiliary electric heater during k (kWh).
$e_{HEAT}(k)$	Electrical consumption in heating mode during k (kWh).
$e_{HVAC}(k)$	Electrical consumption by chiller in refrigeration mode during k (kWh).
$e_{load}(k)$	Total electrical demand during k (kWh).
$e_{ICE}(k)$	Electrical consumption by chiller in ice-making mode during k (kWh).
$\overline{e_b}$	Capacity of battery k (kWh).
k	Time period index, $k = 1, 2, \ldots, K$.
M	A great positive integer.
n_{sa}	Number of solar thermal collectors.
$\overline{p}_{ae}$	Rated power of auxiliary electric heater (kW).
$p_b(k)$	Battery charge (> 0) or discharge (< 0) during k (kW).
$\overline{p_{bo}}$	Maximal discharge rate of battery (kW).
$\overline{p_{bi}}$	Maximal charge rate of battery (kW).
$\underline{p_{bi}}$	Minimal charge rate of battery (kW).

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$\underline{p_{bo}}$	Minimal discharge rate of battery (kW).
$p_c(k)$	CCHP power generated during k (kW).
$\overline{p_c}$	Electrical capacity of CCHP unit (kW).
$\overline{p}_{chiller}$	Rated power of chiller (kW).
$p^d(k)$	Power supplied to loads from grid (> 0) during k (kW).
$p_s(k)$	Solar power generated during k (kW).
$p^u(k)$	Power fed into grid (< 0) during k (kW).
$q_c(k)$	CCHP cooling generated during k (kWh).
$q_h(k)$	Total heating demand during k (kWh).
$q_{hc}(k)$	CCHP heat generated during k (kWh).
$q_i(k)$	Cooling quantity stored in ice storage unit during k (kWh).
$q_{id}(k)$	Cooling quantity supplied by ice storage unit during k (kWh).
$q_{idh}(k)$	Heat quantity supplied by heat storage unit during k (kWh).
$q_{ih}(k)$	Heat quantity stored in heat storage unit during k (kWh).
$q_{io}(k)$	Remaining cooling quantity in ice storage unit during k (kWh).
$q_{ioh}(k)$	Remaining heat quantity in heat storage unit during k (kWh).
$q_{load}(k)$	Total cooling demand during k (kWh).
Q_h	Capacity of heat storage unit (kWh).
Q_{ic}	Capacity of ice storage unit (kWh).
r_s	Horizontal solar radiation (kWh).
s_l	Scenario index of demand profile, $s_l = 1, 2, \ldots, S_l$.
s_s	Scenario index of solar radiation, $s_s = 1, 2, \ldots, S_s$.
t_l	Demanded temperature of hot water (°C).
t_o	Environmental temperature (°C).
t_w	Temperature of municipal water (°C).
$V(k)$	Hot water generated during k (m^3).
$V_c(k)$	Natural gas consumed by CCHP during k (m^3).
V_{ic}	Capacity of water tank (m^3).
$V_o(k)$	Remaining hot water in tank during k (m^3).
$V_s(k)$	Demand of hot water during k (m^3).
$x_b(k)$	Remaining electrical energy in battery during k (kWh).
$\underline{x_b}$	Lower bound of state of charge (SOC) of battery.
$\overline{x_b}$	Upper bound of SOC of battery.
$x_c(k)$	Electrical load ratio of CCHP during k ($x_c(k) = p_c(k)/\overline{p_c}$).
$\underline{x_c}$	Minimal electrical load rate of CCHP.
$\overline{x_c}$	Maximal electrical load rate of CCHP.
x_l	Discrete variable, "1" if utilization time of battery has not exceeded b_l during scheduling horizon, "2" if it exceeds b_l.
$z_b^c(k)$	Discrete variable, "1" if battery is charging during k, "0" otherwise.
$z_b^d(k)$	Discrete variable, "-1" if battery is discharging during k, "0" otherwise.
$z_{bc}^c(k)$	Discrete variable, "1" if battery charge is generating penalty during k, "0" otherwise.
$z_{bc}^d(k)$	Discrete variable, "-1" if battery discharge is generating penalty during k, "0" otherwise.
$z_c(k)$	$z_c(k) = 1$ (or 0) if CCHP is started up (or shut down) during k.
$z_{HVAC}(k)$	$z_{HVAC}(k) = 1$ (or 0) if chiller is in refrigeration mode (or not) during k.
$z_{ICE}(k)$	$z_{ICE}(k) = 1$ (or 0) if chiller is in ice-making mode (or not) during k.
$z_p^d(k)$	Discrete variable, "1" if power is supplied to terminal loads during k, "0" otherwise.
$z_p^u(k)$	Discrete variable, "1" if power is fed into grid during k, "0" otherwise.
$z_{SI}(k)$	$z_{SI}(k) = 1$ (or 0) if cooling is (or not) supplied by ice storage unit.
τ	Time length of a period (hour).
μ_a	Efficiency of solar thermal collectors.
μ_{ae}	Efficiency of auxiliary electric heater.
$\mu_{chiller}$	Efficiency of chiller in ice-making mode.
μ_h	Loss coefficient of heat storage unit.
μ_{lw}	Loss heat coefficient.
μ_q	Loss coefficient of ice storage unit.
μ_w	Conversion coefficient ($\mathrm{kWh/(kg \cdot {}^\circ C)}$).
ρ_w	Density of hot water $(\mathrm{kg/m})^3$.
π_{sl}	Probability of s_l^{th} scenario of demand profile.
π_{ss}	Probability of s_s^{th} scenario of solar radiation.

II. Introduction

BUILDING energy efficiency has attracted a lot of research efforts in recent years since buildings use a significant percentage of energy consumption in our modern society. A building energy system usually consists of multiple energy sources and media such as power distribution grids, autonomous generators (such as combined cooling, heating, and power (CCHP) generating units), renewable energy resources (such as photovoltaic (PV) panels, solar thermal collectors, and wind power generators), various storage devices (such as electrical batteries, ice storage units, heat storage units, and water tanks), and schedulable loads (such as heating, ventilation, and air conditioning (HVAC) systems and room thermal loads controlled by blinds or opening windows) [1], [2], [4]. Various energy sources and loads (such as electricity, natural gas, solar power and thermal generation, cooling, and heating) are correlated or coupled with one another as shown in Fig. 1.

Many efforts have been made in building energy efficiency. Firstly, most studies focus on improving the energy efficiency

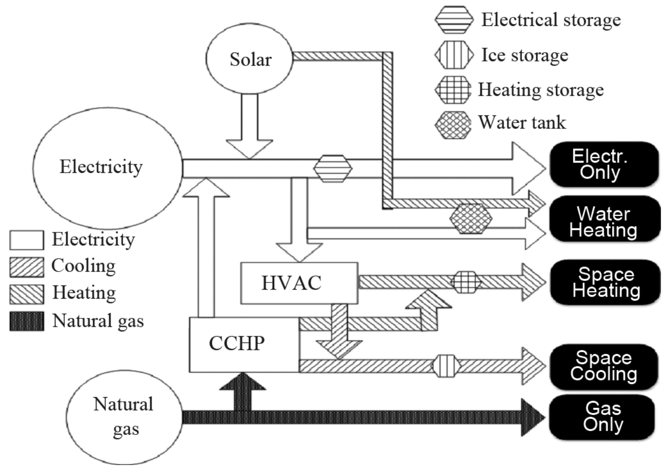

Fig. 1. Multiple energy sources of the building energy system.

of an HVAC system since it uses the most building energy consumption. Huang [1] proposed a method to increase efficiency of the HVAC systems by natural ventilation with information about the outdoor environment. Li *et al.* [2] and Braun [3] showed that an ice storage unit can reduce the operating cost of an HVAC system and the capacity of a chiller. Secondly, some research focuses on improving building energy efficiency through integrated control of terminal loads. Sun *et al.* [4] showed that integrated terminal control and HVAC systems can significantly save energy while satisfying occupant comfort requirements. Tzempelikos and Athienitis [5] revealed an approach to providing the required illuminance and minimizing the energy cost of the lights by jointly controlling blinds and lights. Thirdly, some researchers study the utilization of renewable energy resources in building energy supply systems as well as the usage of microgrid technology in improving energy efficiency of building energy supply systems. Mooney and Kroposki [6] analyzed the potential to save building energy consumption with renewable energy resources. Guan, Xu, and Jia [7] revealed a method to improve operation efficiency of building energy systems through microgrid. Marnay *et al.* [8] proposed an optimization approach for obtaining the control strategy of commercial-building microgrids with the distributed energy resources customer adoption model.

Storage devices play a very important role in reducing energy consumption and cost in building energy systems since they can improve the efficiency of renewable energy resource utilities and the flexibility of time-of-use (TOU) electricity prices. One of the salient features of building energy systems is that thermal energy provided by HVAC systems may take more than 40% of the total building energy consumption. However, few efforts were made to study the building energy system integrated with both thermal and electrical storage devices. In this paper we focus on planning, scheduling, and coordinating different storage devices together with other energy devices in a building energy system facilitated by microgrid technology.

As aforementioned, there are many types of storage devices, and selecting the appropriate storage devices is very important for building energy efficiency based on quantitative performance analysis and comparison. For the management of these devices with the TOU electricity price in a microgrid, the goal is generally to minimize the overall energy cost while satisfying the occupant demands. This problem is very challenging, and few efforts have been made to address the difficulties in evaluating the storage devices in building energy systems. Firstly, the storage devices couple supply and demand across time and evaluation of these devices is nested with complicated scheduling problems. Secondly, the electrical and thermal demand profiles are uncertain since they are based on uncertain occupant movement and behavior. Meanwhile, the demand profiles are also subject to fluctuation of the outdoor environment. Furthermore, the renewable energy supply, such as solar power and thermal generation, is highly uncertain due to solar radiation and weather conditions.

This paper presents a stochastic analysis and optimization problem for the integrated planning and scheduling of the smart building energy systems in a microgrid environment. With the proposed formulation, the best combination and optimal capacities of storage devices such as electrical batteries and ice storage units can be obtained at the planning level. This is very important to design and allocate the storage devices in a smart building energy system. The optimal operating strategy of the building energy system can be obtained at the scheduling level to reduce energy consumption and cost. To deal with the uncertainties effectively, the proposed problem is solved by the scenario tree method using an efficient optimization solver CPLEX, where the uncertainties in the demand profiles and solar radiation are represented through multiple scenarios.

The numerical testing is performed with the electrical and thermal demand profiles taken from our previous work [4] with different weather data. The test results show that, with the proposed model and method, the appropriate types and capacities of storage devices for a specific building can be effectively determined. Through our performance analysis and comparison based on the cases for the three typical temperate and subtropical locations described in the paper, it is found that the thermal storage devices, such as the ice storage unit and the hot water tank, are effective in saving energy costs. But with the TOU electricity price considered in the paper, the current electrical battery used as energy storage may not be economical enough due to its high investment costs and short lifetime. The principles of selecting storage devices are summarized for different conditions. It is also observed that the uncertainties in demand and solar radiation profiles can influence determination of the type and capacity of the storage devices. For example, when the variance of both solar radiation and demand profiles is large, it would be amenable to use electrical batteries to store excess solar power.

The rest of this paper is organized as follows. In Section III, the stochastic problem formulation is presented. In Section IV, the approximate problem is solved by the scenario tree method. In Section V, the proposed method is tested with various numerical cases, and the results on performance and comparison are shown. The concluding remarks then follow.

III. Problem Formulation

The focus of this paper is to study the performance analysis of different energy storage devices by investigating the integrated planning-and-scheduling problem coordinated with other devices in the building energy system while satisfying the occupant requirements. The energy system considered includes a power grid, PV panels, solar hot water system (including solar thermal collectors and an auxiliary electric heater), CCHP unit, HVAC system, electrical battery, water tank, ice storage unit, and heat storage unit. The scheduling horizon is K with discrete time periods. The objective is to minimize the overall cost of electricity, natural gas, and the investment cost of storage devices with TOU electricity prices over the entire lifetime on average for all scenarios in 8760 hours. The forecasted electrical and thermal demand profiles are assumed by the previous work [4] with weather data of different locations. A set of scenarios of demand profiles and solar radiation are generated by the forecasted ones using their distributions.

The integrated planning-and-scheduling problem is to determine the type and capacity of the storage devices and the operating strategies of all energy supplies and storage devices over the scheduling horizon such that the total cost of electricity, natural gas, and the investment cost of storage devices is minimized. It is formulated as the following optimization problem:

$$\begin{aligned}\min J = \Bigg\{ & \sum_{s_l=1}^{S_l} \pi_{sl} \sum_{s_s=1}^{S_s} \pi_{ss} \sum_{k=1}^{K} \big[C^p_{k,s_s,s_l}(c^d_p(k,s_s,s_l), \\ & c^u_p(k,s_s,s_l), p^d(k,s_s,s_l), p^u(k,s_s,s_l), \tau) \\ & + C^n_{k,s_s,s_l}(c_n(k,s_s,s_l), V_c(k,s_s,s_l), \tau) \big] \Bigg\} \\ & + c_{bic} + c_{wic} + c_{qic} + c_{hic} + c_b. \end{aligned} \tag{1}$$

subject to the following constraints. For simplicity, the notation for scenarios of demand profiles and solar radiation is dropped, but the constraints should be satisfied for all scenarios.

i) System constraints

Electrical, cooling, and heating energy balance and requirements represent the balance and requirements of various energy flows between supply and demand. The energy balance and requirement constraints are shown in (2)– (4).

1) Electrical energy balance:

$$\begin{aligned}(p^d(k) + p^u(k) + p_s(k) + p_c(k) - p_b(k)) \cdot \tau = e_{HVAC}(k) \\ + e_{ICE}(k) + e_{HEAT}(k) + e_{load}(k) + e_{ae}(k).\end{aligned} \tag{2}$$

2) Cooling energy requirement:

$$\begin{aligned}q_c(k) + e_{HVAC}(k) \cdot cop(k) + e_{ICE}(k) \cdot copi(k) \\ \geq q_{load}(k) + q_i(k) - q_{id}(k).\end{aligned} \tag{3}$$

In this paper, it is assumed that the heating energy is provided by the HVAC system in winter and the heating energy requirement is similar to (3) as shown in (4).

3) Heating energy requirement:

$$q_{hc}(k) + e_{HEAT}(k) \cdot cop_h(k) \geq q_h(k) + q_{ih}(k) - q_{idh}(k). \tag{4}$$

ii) Cost of electricity and natural gas

1) Operating state of power grid

$$z^d_p(k) + z^u_p(k) \leq 1. \tag{5}$$

2) Cost of electricity:

$$\begin{aligned}0 \leq p^d(k) \leq z^d_p(k) \cdot M, -M \cdot z^u_p(k) \leq p^u(k) \leq 0, \\ C^p_k(c^d_p(k), c^u_p(k), p^d(k), p^u(k), \tau) \\ = (p^d(k) \cdot c^d_p(k) + p^u(k) \cdot c^u_p(k)) \cdot \tau.\end{aligned} \tag{6}$$

3) Cost of natural gas:

$$C^n_k(c_n(k), V_c(k), \tau) = c_n(k) \cdot V_c(k) \cdot \tau. \tag{7}$$

iii) Investment cost of storage devices

$$\begin{cases} c_{bic} = a_b \cdot \overline{e_b} \\ c_{hic} = a_h \cdot Q_h \\ c_{qic} = a_q \cdot Q_{ic} \\ c_{wic} = a_w \cdot V_{ic}. \end{cases} \tag{8}$$

In this paper, the investment costs of storage devices are converted to the scheduling horizon with the parameters obtained from [9], [10] according to their lifetime.

iv) Constraint of battery control

1) Input and output power capacities:

$$\begin{aligned} & z^c_b(k) - z^d_b(k) \leq 1, \\ & z^c_b(k) \cdot \underline{p_{bi}} + z^d_b(k) \cdot \overline{p_{bo}} \leq p_b(k), \\ & p_b(k) \leq z^c_b(k) \cdot \overline{p_{bi}} + z^d_b(k) \cdot \underline{p_{bo}}. \end{aligned} \tag{9}$$

2) Constraint of SOC:

$$\underline{x_b} \cdot \overline{e_b} \leq x_b(k) \leq \overline{x_b} \cdot \overline{e_b}. \tag{10}$$

3) SOC dynamics:

$$x_b(k+1) = x_b(k) + p_b(k). \tag{11}$$

4) Initial and last state of SOC:

$$x_b(0) = x_b(K) = x^0_b \text{ (initialvalue)}. \tag{12}$$

5) Constraint of penalty of battery lifetime:

$$\begin{aligned} & z^c_{bc}(k) - z^d_{bc}(k) \leq 1, \\ & z^c_{bc}(k) - z^{da}_{bc}(k) \leq 1, \\ & z^{ca}_{bc}(k) - z^d_{bc}(k) \leq 1. \end{aligned} \tag{13}$$

$$\begin{aligned} & z^c_b(k) - z^c_b(k-1) = z^c_{bc}(k) + z^{da}_{bc}(k), \\ & z^d_b(k) - z^d_b(k-1) = z^d_{bc}(k) + z^{ca}_{bc}(k). \end{aligned} \tag{14}$$

where $z^{ca}_{bc}(k)$ and $z^{da}_{bc}(k)$ are the assistant parameters to balance (14) when the state of the battery changes from charge (discharge) to idle, since this state transition does not generate penalty.

$$\begin{aligned} (x_l - 1)b_l \leq & \sum_{k=1}^{K} [z^c_{bc}(k) - z^d_{bc}(k)] \\ & \leq x_l \cdot b_l + (x_l - 1)(k - b_l) \\ c_b = & (x_l - 1)\overline{c_b}. \end{aligned} \tag{15}$$

Since the lifetime of battery is limited, the usage cost is appended when the utilization time is more than half of the lifetime.

v) Constraint of CCHP

1) Constraint of operation of CCHP:

$$z_c(k) \cdot \underline{x_c} \leq x_c(k) \leq z_c(k) \cdot \overline{x_c}. \tag{16}$$

2) Output energy of CCHP:

$$\begin{cases} p_c(k) = \overline{p_c} \cdot x_c(k) \\ q_c(k) = (a \cdot x_c(k) + b \cdot z_c(k)) \cdot \tau \\ q_{hc}(k) = (c \cdot x_c(k) + d \cdot z_c(k)) \cdot \tau. \end{cases} \tag{17}$$

3) Consumed rate of natural gas:

$$V_c(k) = (e \cdot x_c(k) + f \cdot z_c(k)) \cdot \tau. \tag{18}$$

Note that the output energy and natural gas consumed by CCHP are fitted by a linear function of electric load rate with operation data. a, b, c, d, e, and f are parameters of CCHP and can be obtained by linear fitting [11]; these parameters depend on the rated power of CCHP.

vi) Constraint of ice storage unit

1) Constraint of chiller mode:

$$\begin{aligned} z_{HVAC}(k) + z_{ICE}(k) &\leq 1 \\ z_{SI}(k) + z_{ICE}(k) &\leq 1. \end{aligned} \tag{19}$$

The chiller can be set to either refrigeration mode or ice-making mode, and the ice storage unit would supply the cooling energy when the chiller is not in ice-making mode.

2) Cooling energy generated in two modes:

$$\begin{aligned} 0 &\leq e_{HVAC}(k) \cdot cop(k) \\ &\leq z_{HVAC}(k) \cdot \overline{p}_{chiller} \cdot \tau \\ 0 &\leq e_{ICE}(k) \cdot copi(k) \\ &\leq z_{ICE}(k) \cdot \overline{p}_{chiller} \cdot \mu_{chiller} \cdot \tau. \end{aligned} \tag{20}$$

3) Remaining cooling dynamics in ice storage unit:

$$\begin{aligned} q_{io}(k+1) = (q_{io}(k) + q_i(k) \\ -q_{id}(k)) \cdot \mu_q \quad q_{io}(k) + q_i(k) \leq Q_{ic}. \end{aligned} \tag{21}$$

vii) Constraint of heat storage unit

1) Heating energy generated in heating mode:

$$0 \leq e_{HEAT}(k) \cdot cop_h(k) \leq \overline{p}_{chiller} \cdot \tau. \tag{22}$$

2) Remaining heating dynamics in heat storage unit:

$$\begin{aligned} q_{ioh}(k+1) = (q_{ioh}(k) + q_{ih}(k) \\ -q_{idh}(k)) \cdot \mu_h \quad q_{ioh}(k) + q_{ih}(k) \leq Q_h. \end{aligned} \tag{23}$$

viii) Constraint of solar hot water system

1) Power capacities of auxiliary electric heater:

$$0 \leq e_{ae}(k) \leq \overline{p}_{ae} \cdot \tau. \tag{24}$$

2) Remaining water dynamics:

$$V_o(k+1) = V_o(k) + V(k) - V_s(k) \tag{25}$$

$$V_o(k) + V(k) \leq V_{ic}. \tag{26}$$

3) Water production of solar hot water system:

$$\begin{aligned} \mu_a \cdot r_s(k) \cdot n_{sa} + \mu_{ae} \cdot e_{ae}(k) = \mu_w \rho_w (V(k) \cdot (t_l - t_w) \\ +\mu_{lw}(V(k) + V_o(k)) \cdot (t_l - t_o(k))). \end{aligned} \tag{27}$$

ix) Constraint of PV panels [12]

1) Electric power output of PV panels:
A PV module is composed of PV cells in series. Multiple modules in series-parallel connections form the PV array. The output power of the entire PV panel is:

$$p_s(k) = U_s(k) I_s(k) = N_s N_{ss} N_{pp} V_{cell}(k) I_{cell}(k). \tag{28}$$

where N_s is the number of PV cells in a PV module, N_{ss} is the number of series PV modules, and N_{pp} is the number of parallel PV module strands.

2) I-V equation of PV cell in PV panels:

$$\begin{aligned} I_{cell}(k) = I_L(k) \\ - I_o(k) \left[\exp\left(\frac{V_{cell}(k) + I_{cell}(k) R_s}{a} - 1 \right) \right] \\ - \frac{V_{cell}(k) + I_{cell}(k) R_s}{R_p}. \end{aligned} \tag{29}$$

The derivative of PV cell power to PV cell voltage is zero at the maximum power point (MPP). So we have

$$\begin{aligned} &\left.\frac{d(VI)}{dV}\right|_{mpp} = I_{cell}(k) + V_{cell}(k) \left.\frac{dI}{dV}\right|_{mpp} = I_{cell}(k) \\ &+ V_{cell}(k) \frac{-I_o(k) R_p \exp(\frac{V_{cell}(k) + I_{cell}(k) R_s}{a}) - a}{a R_p + I_o(k) R_s R_p \exp(\frac{V_{cell}(k) + I_{cell}(k) R_s}{a}) + a R_s} \\ &= 0. \end{aligned} \tag{30}$$

where $I_{cell}(k)$ and $V_{cell}(k)$ are the output current and voltage of PV cells during k, respectively, $I_L(k)$ is the current generated by the incident light during k, $I_o(k)$ is the reverse saturation or leakage current of the diode during k, R_s and R_p are the equivalent series resistance and parallel resistance of the cell, respectively, and a is the modified ideality factor. All the aforementioned parameters depend on solar radiation, cell surface, temperature, and the optical air mass, and can be calculated as shown in [12].

IV. Solution Methodology

A. Linearization of HVAC Formulation

In order to simplify the formulation of the HVAC system (including the ice storage unit and the heat storage unit), the coefficient of performance (COP) is used to describe the refrigerating (or heating) efficiency of the HVAC system. The cooling (or heating) supplied by the HVAC system is the product of the COP and its electrical energy consumption, and the COP varies with the electric load rate of the chiller. Note that the electric load rate is the ratio of the operating power and the nominal power of a chiller, and it is a no-dimension variable. In this paper, the COP of the HVAC system is assumed to be a piecewise linear function of the electric load rate for simplification. So the rate of cooling supplied by the HVAC system is the piecewise parabolic function of the electric load rate as shown in Fig. 2. To simplify, the parabolic function is piecewise linearized in this paper. The refrigeration mode of the HVAC system is used as

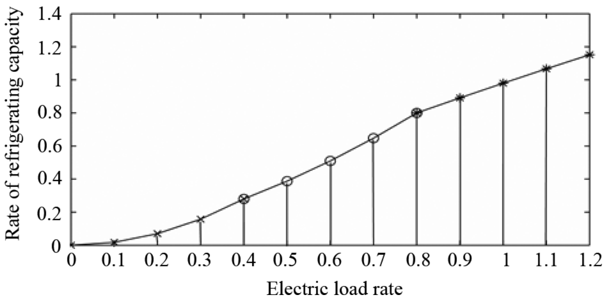

Fig. 2. The rate of cooling supplied as a function of electric load rate.

an example to present the linearization method. The ice-making mode and heating mode conditions are omitted since they are similar to that of the refrigeration mode.

As shown in Fig. 2, the electric load rate is divided into I segments. It is assumed that the rate of cooling supplied by the HVAC system is a linear function of the electric load rate in each segment. With the parabolic function, the minimal and maximal rate of cooling supplied by the HVAC system in each segment can be obtained. The slope of each segment then can also be determined using the minimal and maximal values. So (20) can be linearized as follows.

$$\begin{aligned} &R_{\min}(i)\cdot z_p(k,i) \le R(k,i) \le R_{\max}(i)\cdot z_p(k,i), \\ &q_{\min}(i)\cdot z_p(k,i) \le q(k,i) \le q_{\max}(i)\cdot z_p(k,i), \\ &q(k,i) = q_{\min}(i)\cdot z_p(k,i) \\ &\qquad\qquad + s_p(i)\cdot (R(k,i) - R_{\min}(i)\cdot z_p(k,i)). \end{aligned} \tag{31}$$

$$\begin{cases} z_{HVAC}(k) = \sum_{i=1}^{I} z_p(k,i) \\ e_{HVAC}(k) = \sum_{i=1}^{I} R(k,i)\cdot \overline{p}_{chiller} \\ e_{HVAC}(k)\cdot COP(k) = \sum_{i=1}^{I} q(k,i)\cdot \overline{COP}\cdot \overline{p}_{chiller} \end{cases} \tag{32}$$

where $R(k,i)$, $q(k,i)$ are the electric load rate and rate of cooling supplied by the HVAC system in i segment during k, respectively, $R_{\min}(i)$ and $R_{\max}(i)$ are the minimal and maximal electric load rate in i segment, respectively, $q_{\min}(i)$ and $q_{\max}(i)$ are the minimal and maximal rate of cooling supplied by the HVAC system, respectively. $z_p(k,i)$ is the integer variable, where $z_p(k,i) = 1$ means that there is an electric load rate in the segment i during k; otherwise, $z_p(k,i) = 0$. $s_p(i)$ is the slope of i segment. $\overline{COP}$ is the rated value of the COP in refrigeration mode. Note that the range of the electric load rate and the refrigeration capacity rate in each segment are confirmed in the first and the second formula in (31), and the refrigeration capacity rate can be calculated with the third formula. In (32), the first formula shows that if the chiller works in refrigeration mode, the refrigeration capacity should only be in one segment during k, according to the first formula in (19). The energy consumption of the HVAC system and the cooling supplied by the HVAC system also can be calculated with the second and the third formula in (32), respectively.

In this paper, the CPLEX solver is applied to solve the proposed problem. It is designed to solve large, difficult problems efficiently with the minimal user intervention. Access is provided to the branch-and-cut solution algorithms for linear, quadratically constrained, and mixed integer programming problems with computation and memory- intensive tasks [13]. The above mixed integer programming problem of (1)–(32) is solved by this CPLEX solver with demand and solar radiation profiles.

B. Solution to Stochastic Problem by Scenario Tree Method

In practice, there are significant uncertainties in demand profiles of building energy systems since electrical demand and thermal demand (such as lighting, energy consumption of fan coin units, cooling units, etc.) are uncertain due to uncertain occupant movement and behavior as well as weather conditions. Moreover, solar power and thermal generation are also uncertain as they are closely related to the solar radiation and weather conditions. Therefore, it is necessary to consider the above planning-and-scheduling problem, keeping in mind the uncertainties in both the supply and demand side, to obtain the best combination and optimal capacities of storage devices, as well as the schedule of all controllable devices in a building energy system with the best expected cost.

When demand profiles and solar radiation are forecasted, it is likely that the actual demand profiles and solar radiation are significantly different from the forecasted values [14]. For the proposed problem with a clear multi-stage stochastic decision structure, the scenario tree method is effective in handling the uncertainties in the demand profiles and solar radiation with multiple scenarios [14], [15]. A scenario is used to describe a specific set of demand profiles or solar radiation, which is either randomly generated with environmental data according to the significant demand profile, or manually built according to heuristics information of the problem. In order to manage the aforementioned uncertainties, two sets of scenarios should be established, which are scenarios of demand profiles (including electrical demand and thermal demand) and of solar radiation. Note that the scenarios of solar power and thermal generation can be obtained from solar radiation in (28)–(30) and (27), respectively. Furthermore, in order to obtain a good solution for the proposed problem, we need to establish different sets of representative scenarios. Then the stochastic optimization problem is solved with the average cost of all scenarios. Considering the uncertainties in demand profiles and solar radiation, this formulation is necessary for solving the stochastic problem by the scenario tree method.

In particular, if the demand profiles and solar radiation are known in advance or they vary only slightly, the stochastic problem can be approximately simplified as a deterministic model with one scenario of the forecasted demand profiles and solar radiation. The best combination and optimal capacities of storage devices with the forecasted demands and solar radiation are also obtained by solving the deterministic problem, and they are compared with the results from solving the stochastic problem with multiple scenarios. A numerical case of the procedure to solve the stochastic problem by the scenario tree method and the comparison to the forecasted demand and solar radiation will be presented in the next section.

V. Numerical Results

The problem based on an office building with three demand profiles is tested at Guangzhou (with hot and humid weather and solar radiation with little variation), Beijing (with four distinct seasons), and Harbin (with cold weather and solar radiation with little variation), China, and the results are presented in this section. The building energy system includes the power grid,

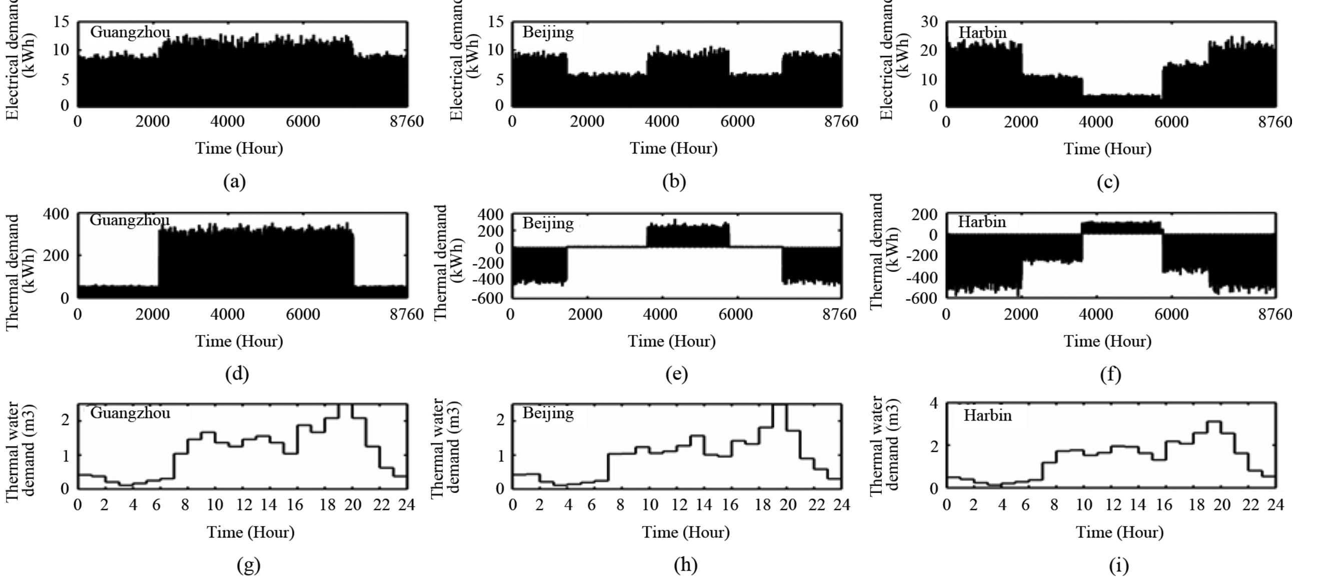

Fig. 3. (a) Electrical demand at Guangzhou. (b) Electrical demand at Beijing. (c) Electrical demand at Harbin. (d) Thermal demand at Guangzhou. (e) Thermal demand at Beijing. (f) Thermal demand at Harbin. (g) Hot water demand at Guangzhou. (h) Hot water demand at Beijing. (i) Hot water demand at Harbin.

one CCHP unit (with a rated power of 50 kW), PV panels (consisting of two 3-parallel modules with 54 cells in series), a solar hot water system (containing 10 solar thermal collectors and one auxiliary electric heater with rated power of 96 kW), one chiller of a HVAC system (with capacity of 200 kWh), one battery, one ice storage unit, one water tank, and one heat storage unit. Testing is performed for over one year. The weather data, including the solar radiation and outdoor temperature of the aforementioned locations, is obtained from [16].

It is assumed that the occupants work in the building from 7:00 to 23:00 everyday. The annual electrical and thermal demand profiles are obtained by solving the terminal control problem according to the occupant comfort requirements [4] with 2010 weather conditions of the aforementioned locations. With the given comfort level (indoor temperature: $[22\ ^{\circ}\mathrm{C},\ 26\ ^{\circ}\mathrm{C}]$ in summer, $[16\ ^{\circ}\mathrm{C},\ 20\ ^{\circ}\mathrm{C}]$ in winter, $[18\ ^{\circ}\mathrm{C},\ 22\ ^{\circ}\mathrm{C}]$ in transitional seasons; indoor humidity: $[50\%,\ 60\%]$; concentration of CO2: $[0,\ 1300\ \mathrm{ppm}]$; $\mathrm{luminance} > 400\ \mathrm{lx}$), the annual electrical and thermal demand profiles are obtained, and they are shown in Fig. 3. In Figs. 3(d)–3(f), positive values of the thermal demand curve are used for the cooling demand and negative values for the heating demand. The everyday hot water demand profile is obtained from [17]. It is assumed to be the same everyday over the whole year at the three locations as shown in Figs. 3(g)–3(i), respectively, since hot water demand varies little. The curves of solar radiation for the selected three sites are also shown in Figs. 4(a)–4(c), respectively.

In this case, the price of natural gas is $2.05\ \mathrm{RMB}/\mathrm{m}^3$, and the price of electricity fed into the grid is 0.457 RMB/kWh. The TOU price of electricity supplied to terminal loads is shown in Table I[18].

In this paper, the lifetime of the battery, the ice storage unit, the heat storage unit, and the water tank are defined as 3 years, 10 years, 10 years, and 20 years, respectively. The investment costs of the storage devices are converted to the scheduling horizon (one year in this case) with the parameters obtained from [9], [10] according to their lifetime. The investment cost per kWh of the battery, the ice storage unit, and the heat storage unit can be calculated and they are 175.2 RMB/kWh, 21.9 RMB/kWh, and 32.9 RMB/kWh, respectively. The investment $\mathrm{cost\ per\ m}^3$ of the water tank is also determined to be $1241\ \mathrm{RMB}/\mathrm{m}^3$.

First, the uses of storage devices are analyzed and the results are shown in Section V-A. Using the obtained annual demand profiles of three locations, the performance analysis of storage devices is revealed, and the selection rules of storage devices at different locations are also discussed in Section V-B. Next, according to the best combination and optimal capacities of

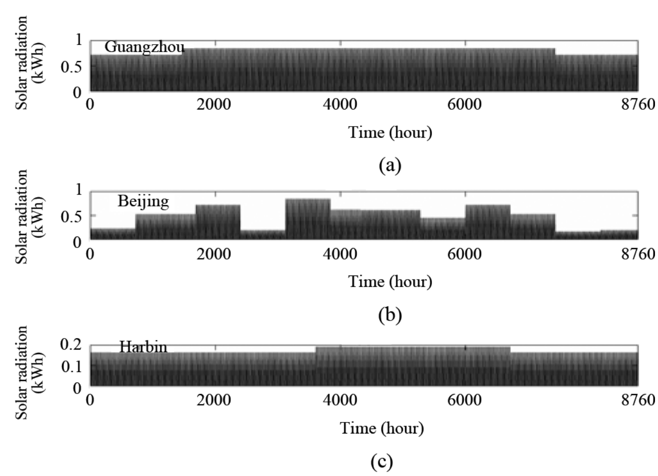

Fig. 4. (a) Solar radiation at Guangzhou. (b) Solar radiation at Beijing. (c) Solar radiation at Harbin.

TABLE I
TOU ELECTRICITY PRICE

PERIOD	PRICE (RMB/KWH)
0:00-7:00	0.3515
7:00-11:00	0.8135
11:00-19:00	0.4883
19:00-23:00	0.8135
23:00-24:00	0.3515

storage devices obtained from Section V-B, the operating strategies of storage devices and their contribution to the power grid are then shown in Section V-C. Finally, for the problem with uncertainties, the scenarios of demand profiles and solar generation are generated randomly with the forecasted demand profiles and solar radiation. The solution is obtained by solving the problem with the expected cost in all scenarios jointly. Furthermore, the comparison between one scenario of the forecasted demand profiles and solar radiation and the multiple scenarios in the stochastic formulation is represented in Section V-D.

A. Usage of Storage Devices

First, the usage of the water tank is analyzed. We assume hot water is stored in the tank and heated by an auxiliary electric heater. The investment cost of one m^3 of water tank considering depreciation is 3.4 RMB per day. Producing one m^3 of hot water (at 60 °C) requires 30 kWh of electrical energy. One m^3 of hot water is produced during lower-price periods (0.3515 RMB/kWh) and then consumed during peak-price periods (0.8135 RMB/kWh), 10.46 RMB of the cost could be saved. However, if the electric heater is supplied by generated solar power, 21 RMB is saved. Both the unit investment cost of the water tank and the price difference between water production and consumption periods could be defined as independent variables. The cost saved is thus a bi-linear function of the two independent variables. We can easily find that there are cost savings by using the water tank as long as the unit investment cost is not 30 times more expensive than the differences of peak-valley electricity prices. In our case, the unit investment cost is about seven times of the peak-valley price difference. Therefore, the water tank is very effective in saving building energy cost when there is hot water demand in peak-price periods.

Similarly, the usage of ice storage unit for the HVAC system is discussed. We assume that the COP rate of the HVAC system is 0.8 when the chiller is in refrigeration mode as well as in ice-making mode. Generating one kWh of cooling energy requires 0.42 kWh of electrical energy in refrigeration mode and 0.71 kWh of electrical energy in ice-making mode. The unit investment cost of the ice storage unit is 0.06 RMB/kWh per day. In general, the chiller is in ice-making mode during lower-price periods, and the ice storage unit supplies the cooling energy in peak-price periods. So 0.032 RMB/kWh of the cost could be saved this way. However, the chiller in ice-making mode always operates on full power, but the power of the chiller in refrigeration mode is determined by the cooling load. Hence, the COP of the chiller in ice-making mode is generally larger than it in refrigeration mode. Therefore, the cost saved is larger than 0.032 RMB/kWh in practice. The cost saved is shown as a bi-linear function of the price during the ice-making and refrigeration periods in Fig. 5. It is found that the ice storage unit is economical when used in a building energy system with TOU prices. Using the heat storage unit is similar to using the ice storage unit, so in this paper, it is omitted.

The battery is used in two situations for building energy savings in general. First, it charges during lower-price periods and discharges during peak-price periods. Second, it is charged through the generation of solar power and discharged in the peak-price periods. The cost-saving function for one unit of energy is shown in Fig. 6. It is found that the battery was economical when differences of peak-valley electricity prices is larger than 0.48 RMB/kWh since the unit investment cost

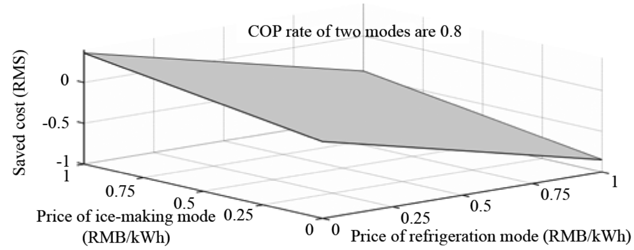

Fig. 5. Usage condition of the ice storage unit.

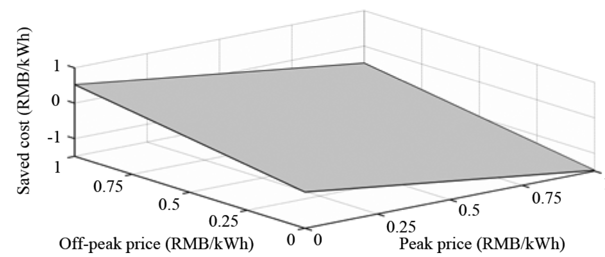

Fig. 6. Usage condition of battery.

of the battery is 0.48 RMB/kWh in this paper (assuming the battery is ideal and the conversion efficiency is 1).

Secondly, the generation of solar power is "free" as mentioned, and it is economical to use the battery since the investment cost of the battery is less than the peak price. However, generated solar power can be used to supply electrical loads (including battery charging), as well as be converted into cooling energy or hot water. Consider that during the highest solar radiation periods (12:00–14:00), the electricity price is 0.4883 RMB/kWh. 0.4883 RMB of the cost can be saved if one kWh of generated solar power is supplied to the electrical loads. When the same amount of solar power is stored in the battery, in the ice storage unit (converted to cooling energy), and in the water tank (converted to hot water), 0.3335 RMB, 0.68 RMB, and 0.8135 RMB of the cost could be saved, respectively, if the stored energy is used in peak-price periods. Therefore, usage generated solar power is prioritized as follows: producing hot water, producing ice, supplying to the electric loads, and charging the battery, all dependent on their capacities. In other word, it is economical to use the battery when there is more solar energy than needed for the first three requirements.

B. Allocation of Storage Devices and Energy Efficiency

The focus of this subsection is to discuss the performance analysis and selection criteria of the storage devices. The formulation is approximated as a deterministic model of one scenario of the forecasted demand profiles and solar radiation without considering the uncertainties in demand profiles and solar radiation. With the 2010 weather data, the forecasted demand profiles and solar radiation are determined. By using the aforementioned electrical, thermal, and hot water demands of the three locations, the CPLEX solver is applied to solve the problem of (1)–(32) with the error gap set as 0.01 for different weather conditions. The best combination and optimal capacities can be then obtained for the three locations, respectively, and the results are shown in Table II. This computational time is about 780 seconds on average on a Windows PC with 3.2 GHz and 2 GB memory.

In Guangzhou, there is no extra generated solar power to store in daytime because of the high cooling demand year long. Therefore, there is no need for an electrical battery. The heat storage unit is also not needed since there is no heating demand.

TABLE II
OPTIMAL COMBINATION OF STORAGE DEVICES AT DIFFERENT LOCATIONS

STORAGE DEVICES	OPTIMAL CAPACITY OF STORAGE DEVICE		
	Guangzhou	Beijing	Harbin
Battery	0 kWh	115 kWh	0 kWh
Water tank	10.8 m^3	9.87 m^3	11.2 m^3
Ice storage unit	1348 kWh	683 kWh	124 kWh
Heat storage unit	0 kWh	858 kWh	1022 kWh

TABLE III
OVERALL COST WITH DIFFERENT COMBINATIONS OF STORAGE DEVICES

COMBINATIONS OF STORAGE DEVICES	OVERALL COST (RMB)		
	Guangzhou	Beijing	Harbin
Include all storage devices	313941	491969	596822
Exclude all storage devices	519114	677095	868087
Battery	488410	640674	813963
Water tank	373109	548957	752262
Thermal storage unit	437444	611107	695124
Battery + water tank	355973	538821	727035
Battery + thermal storage unit	426473	590809	670672
Water tank + thermal storage unit	313941	502095	596822

Therefore, the best combination of storage devices is the water tank and the ice storage unit. However, in Beijing, there are four distinct seasons, and both the ice and heat storage units are needed in the building energy system since both cooling and heating demand exist. In addition, the solar radiation and demand profiles fluctuate significantly during transitional seasons. It is possible to use the extra solar power to charge the battery. Therefore, the combination of the battery, the water tank, the ice storage unit, and the heat storage unit can be used. In Harbin, since the heating demand is present most of the year while a little cooling energy is needed in the summer, the ice and heat storage unit are both needed, but the capacity of the ice storage unit is relatively small. Furthermore, solar radiation is so low that not enough solar power is available to charge the battery. Therefore, the combination of the water tank, the heat storage unit, and the ice storage unit is the best choice. In order to summarize the selection criteria of the storage devices in detail, we test the performances in the different combinations over one year, and the results are shown in Table III. Note that the ice storage unit and the heat storage unit are considered to be an ensemble thermal storage unit to analyze their entire efficiency.

In this paper energy efficiency is used to analyze the performance of the storage devices. The energy efficiency of a specific combination of storage devices is defined as the ratio of overall cost savings with the above storage devices to that without these devices.

First, a single storage device is tested. The battery energy efficiency of Guangzhou, Beijing, and Harbin is only 5.9%, 5.4%, and 6.2%, respectively. It is found that the battery is insensitive to differences in weather conditions, but is relatively inefficient in reducing building energy cost. The energy efficiency of the thermal storage unit is 15.7%, 9.7%, and 19.9% at Guangzhou, Beijing, and Harbin, respectively. When there is heavy cooling demand in the summer, the chiller should be set to refrigeration mode, so the ice storage unit only can lead to energy savings with the TOU prices. However, in the winter, the heating demand for the HVAC system may be lower in the daytime so that the heat supplied by the solar energy may be partially stored in the heat storage unit. This is why the energy efficiency of thermal storage in Guangzhou is less than that in Harbin. It is also found that thermal demand has a major impact on selecting the thermal storage unit, and its energy efficiency is proportional to the thermal demand, including cooling and heating energy. The water tank has good performance in energy efficiency of 28.1%, 18.9%, and 13.3% in Guangzhou, Beijing, and Harbin, respectively. The energy efficiency of the water tank in Harbin is low since the solar radiation and the temperature of municipal water are both low. It is also found that the performance difference between the locations is very large. The major factors affecting the energy efficiency of the water tank are solar radiation and weather conditions. The standard deviation of the energy efficiency between different locations is 38%, thus it is relatively sensitive under the different weather conditions. The efficiency gradually decreases with solar radiation and outdoor temperature. Therefore, the water tank is suitable for regions with high solar radiation and outdoor temperature.

Secondly, the performance of a combination of two types of storage devices is tested. The energy efficiency of the combination of the water tank and the thermal storage unit is largest for all three possible combinations of two storage devices at the different locations. The results in Guangzhou and Harbin are the same between the combination of the water tank and the thermal storage unit and the solution obtained by the proposed method. It again indicates that using the battery is not economical at these locations due to their corresponding demand profiles and solar radiation.

In conclusion, some rules for selecting the type of storage devices with specific demand profiles and solar radiation are summarized as follows. The water tank, the ice storage unit, and the heat storage unit should be selected in a building energy system since they have good performance in building energy savings at all locations. The capacity of the water tank should be selected while considering solar radiation and weather data. The water tank is suited for regions with high solar radiation and outdoor temperature, such as low latitude regions. The capacity of the thermal storage unit should be selected while considering thermal demand. And the thermal storage unit is recommended for regions with high thermal demand, such as low latitude regions and high latitude regions. The energy efficiency of the battery is less than that of other storage devices since its investment cost is high and the lifetime is short. But the battery could be used to store the excess solar power in regions with highly fluctuant solar radiation such as those with distinct seasons. In addition, if the battery is used in the building energy system, it can help in balancing the fluctuation of generated renewable power and also can be used in emergencies.

It is known that the capacities of storage devices have an impact on energy efficiency. A tradeoff between the capacity and investment cost of the storage device should be made. The proposed method has good performance in managing this tradeoff with the demand profiles and solar radiation. The proposed method is very effective for choosing the best combination and optimal capacities of storage devices with specific demand profiles and solar radiation under different weather conditions.

C. Operating Strategies of Storage Devices and Their Contribution to the Power Grid

The optimal operating strategy of each storage device is presented in this subsection. Using the combination and capacities from Section V-B, everyday operating strategies of the storage devices are obtained by solving the problem with the proposed

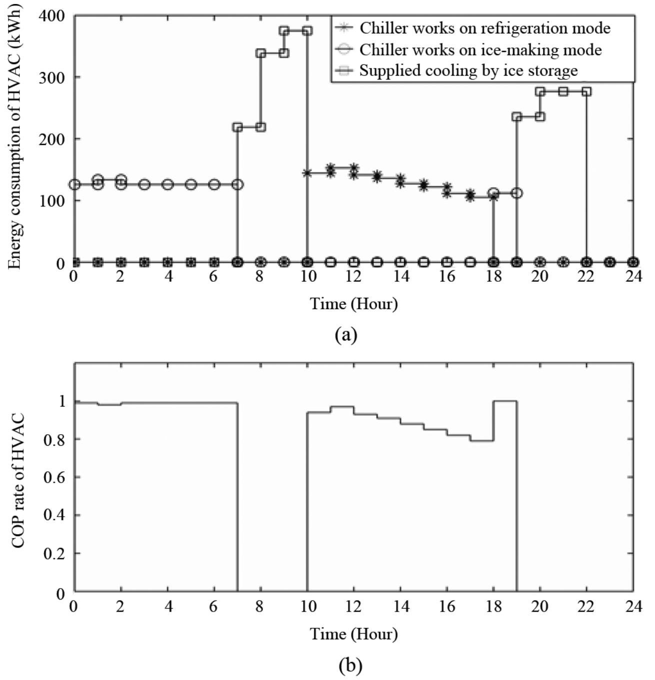

Fig. 7. (a) Operating strategy of the ice storage unit. (b) COP of the HVAC system.

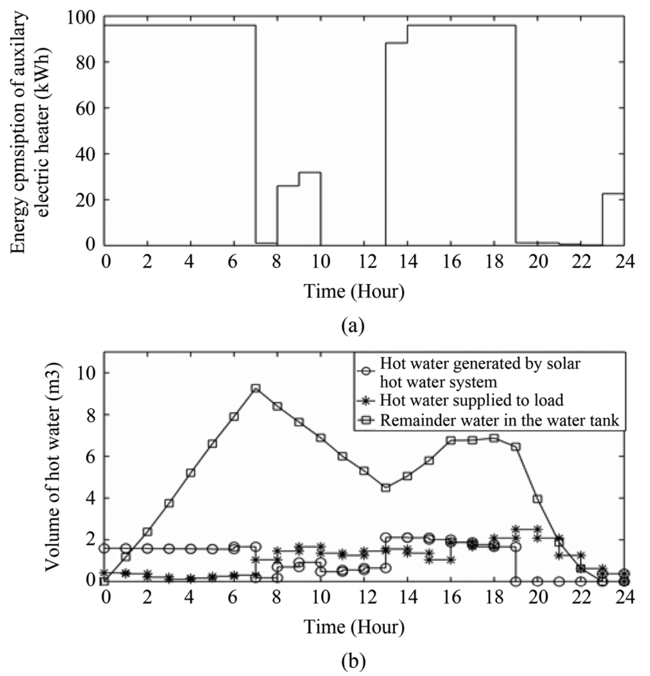

Fig. 8. (a) Operating strategy of the auxiliary electric heater. (b) Dynamic process of the water tank.

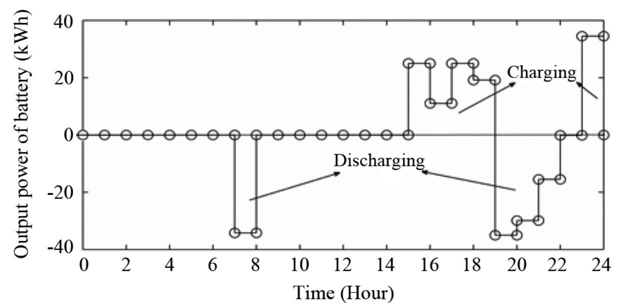

Fig. 9. Operating strategy of the battery.

method. Since the operating strategies are similar despite different locations, only one summer day in Beijing is used as an example to demonstrate the characteristics of operating strategies.

The operating strategy of the HVAC system is shown in Fig. 7(a). The chiller of the HVAC system works in ice-making mode during lower-price and lower-load periods (such as 0:00–7:00). During these periods, most of the cooling quantity generated by the chiller is stored in the ice storage unit whereas the rest is supplied to the loads. Then the cooling quantity stored in the ice storage unit is supplied to the loads during peak-price periods (such as 7:00–10:00 and 19:00–22:00) to reduce the overall cost. The chiller is in refrigeration mode in the daytime since the cooling load is large. The chiller is set to ice-making mode from 18:00 to 19:00 since the cooling load is relatively small so that the COP is low if the chiller switches to refrigeration mode. So comparing the COP function and energy consumption for both modes, it is found that the chiller in ice-making mode is relatively economical in this period. The COP of the HVAC system during the whole scheduling horizon in this case is in the high efficiency interval (0.77–1) as shown in Fig. 7(b). It illustrates that the ice storage unit can be used not only to save building energy cost, but also to improve the efficiency of the HVAC system. For the heat storage unit, the same conclusion is obtained, so it is omitted here.

The operating strategy of the solar hot water system is shown in Fig. 8. In Fig. 8(a), the auxiliary electric heater operates at full capacity to store the hot water in the tank [as shown in Fig. 8(b)] during lower-price periods (such as 0:00–7:00). During peak-price periods (such as 7:00–11:00 and 19:00–23:00), the auxiliary electric heater is shut down or only used to remain warm. However, from 8:00–10:00, the electric heater should be started up since solar radiation is too low to produce enough hot water. From 13:00–19:00, the electric heater is at full capacity to store hot water, and this water is used in the nightly peak-price periods.

The operating strategy of the battery is shown in Fig. 9. The battery is discharging from 7:00 to 8:00 since it is a peak-price period and there is initial power energy in the battery. When there is excess solar power such as from 15:00 to 19:00, the battery is fully charged by solar power. And it is discharged during peak-price periods (such as 19:00–22:00). The battery is generally charged by generated solar power and discharged in nightly peak-price periods.

By using these operating strategies, the storage devices can be used not only to reduce the overall building energy cost, but also to adjust the power grid. The impact of storage devices on shifting peak and valley is discussed as follows. The difference between the power load of the distribution grid with and without the above storage devices over the day is used to demonstrate their contribution to the power grid, as shown in Fig. 10. About 35% of the power load in peak-load periods is shifted to valley-load periods with the storage devices. And the difference between the power in peak-load periods and in lower-load periods is also reduced. Thus, the storage devices have good performance in adjusting the power grid. Furthermore, the investment cost and installed capacity of the power plant and its emission of CO_2 can be also reduced.

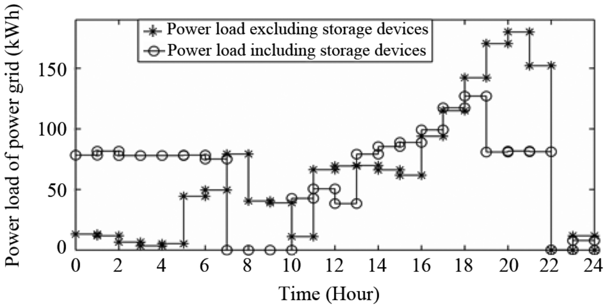

Fig. 10. Impact of storage devices on the power grid.

TABLE IV
THE OPTIMAL SOLUTIONS WITH UNCERTAINTIES AT DIFFERENT LOCATIONS

LOCATIONS	Guangzhou	Beijing	Harbin
OVERALL COST (RMB)	342109	509223	610482
OPTIMAL CAPACITY OF STORAGE DEVICES			
Battery (kWh)	0	120.3	75.6
Water tank (m^3)	11.9	11.3	10.7
Ice storage unit (kWh)	1398.6	844.5	147.2
Heat storage unit (kWh)	0	936.8	1138.2

D. Stochastic Problem Solved by the Scenario Tree Method

Through the above analysis, it is found that demand profiles and solar radiation have a huge impact in the selection of the types and capacities of the storage devices. To find a good solution, the uncertainties in demand profiles and solar radiation should be considered. In this paper, the scenario tree method is used to solve the stochastic optimization problem. A set of scenarios of demand profiles and solar radiation is used to describe their uncertainties. The solution should have good average performance over all scenarios. In this problem, the major uncertainties are electrical and thermal demand profiles and solar radiation. To describe their uncertainties, a set of 5 scenarios of the demand profiles and a set of 5 scenarios of the solar radiation are randomly generated with the forecasted demand and solar radiation, respectively. The demand profiles and solar radiation are both assumed to follow independent normal distribution, and the scenarios of the demand profiles are within 5% standard deviation and solar radiation within 20% standard deviation of their forecasted values, respectively. The probability of each scenario is assumed to be same in this paper. In other words, π_{sl} and π_{ss} are equal to 1/5 in this case. Note that the aforementioned annual demand profiles and solar radiation at three locations are assumed to be the forecasted ones.

The above problem is solved with the minimum average cost of all scenarios. The error gap is set to be 0.01. The optimal average cost and the best combination of storage devices at different locations are shown in Table IV. The computational time is about 27 000 seconds on a Windows PC with 3.2 GHz and 2 GB memory.

As seen in Table IV, some differences in the best combination and optimal capacities between the solutions obtained in Section V-B by the simplified deterministic problem (with one scenario of the forecasted demand profiles and solar radiation) and the solutions for the stochastic problem (with multiple scenarios) were found. For example, the optimal capacities of the battery in Harbin determined by the two methods are different. So we are interested in comparing the performance of the simplified deterministic problem with the forecasted scenario with that of the stochastic problem with multiple scenarios. The best combination and the optimal capacities of these two methods at Beijing are tested in several other scenarios, as shown in Table V. It is seen that the performance of the stochastic problem with the multiple scenarios is better in the major scenarios, especially in the scenarios with larger standard deviation. But, in general, the performance of the simplified deterministic problem with one scenario of the forecasted values is still very good and it is only less than 7% while the computational time is one over thirty-five in comparison to the multiple scenarios in the stochastic formulation.

TABLE V
THE PERFORMANCE COMPARISON OF USING ONE FORECASTED SCENARIO AND MULTIPLE SCENARIOS AT BEIJING

Scenario (% STD of demand, solar radiation to their means)	Cost by using simplified problem with the forecasted value (RMB)	Cost by using multiple scenarios (RMB)
5%, 15%	502369	506895
5%, 20%	508976	496319
5%, 25%	498567	484878
10%, 15%	496537	501342
10%, 20%	489953	466011
10%, 25%	507854	475459
15%, 15%	511231	482878
15%, 20%	509984	482324
15%, 25%	512347	477388

VI. CONCLUSIONS

In this paper, we study the performance analysis and comparison of different energy storage devices in building energy systems in a microgrid environment. The building energy system operation is formulated as an energy cost minimization problem with storage devices and other devices in the system. The uncertainties in demand profiles and solar radiation are considered, and a stochastic optimization problem is formulated. The scenario tree method is applied to solve the problem. Numerical results demonstrate that the proposed method is effective in selecting the best combination and optimal capacities of the storage devices, and in obtaining the optimal operating strategy of each device in the building energy system. It is found that thermal storage units and water tanks are effective in saving energy cost in all scenarios, but the electrical battery may not be economical for use due to its high investment cost and short lifetime. Based on the above analysis, rules for selecting storage devices at a specific location can be determined. By comparing the simplified model of one scenario of the demand and solar radiation profiles to the multiple scenarios in the stochastic formulation, we found that it would be sufficient in many cases to obtain the best combination of storage devices with the forecasted demand and solar radiation efficiently without using stochastic formation.

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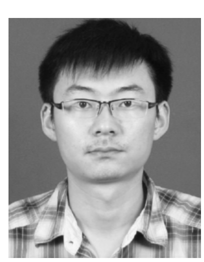

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