Joint Optimization of Battery Energy Storage System and Fans for Frequency Reserve Capacities Allocation and Day-Ahead Energy Management

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***Abstract*— In this paper, we propose a novel optimization strategy for energy-efficient day-ahead energy management and economic power reserve capacity allocation for frequency regulation, by jointly utilizing battery energy storage systems (BESSs) and demand-responsive (DR) fans at the distribution level. Specifically, we consider a smart building with renewable energy integration. The building owns a BESS and is willing to take part in frequency regulation service by allocating a proportion of its BESS capacity as power reserve capacity and receiving monetary reservation fee in return. Due to the high cost of BESS, its limited capacity, and significant degradation caused by excessive charging and discharging, we consider DR fans as a viable low-cost capability of the smart building for energy cost saving and frequency regulation. Particularly, we consider modern fans of the heating, ventilation, and air conditioning (HVAC) systems that can vary their speeds (and thus energy consumption), subject to satisfying user comfort constraints. Simulations results based on the real renewable energy and load data show that our proposed joint optimization strategy is effective in reducing the total energy cost of the building and at the same time providing a higher power reserve capacity to the grid.**

***Index Terms*—Energy management, frequency regulation, energy storage system, fans, HVAC system, optimization.**

I. Introduction

The world-wide electrical energy consumption has been increasing for the last several decades. A study by the US energy information administration (EIA) reported that the worldwide energy consumption will grow by 56% from 2010 to 2040 [1]. An appealing sustainable solution to this concern is to widely integrate renewable energy sources into power systems and satisfy the demand of users locally. However, renewable energy sources, such as solar and wind, are both intermittent and stochastic in general; thus, result in imbalanced supply and cause frequency and/or voltage fluctuations [2]. Hence, it is crucial to not only tackle the power fluctuations of the renewable energy generation with energy-efficient solutions but also provide a larger power reserve capacity for frequency regulation purpose. The approach of mitigating renewable energy deficit from conventional generation sources such as diesel generators, and also the conventional reserve services enabled by fast/moderate ramping generation units, e.g., diesel and gas-turbine generators, cause high operational cost. Thus, other low-cost, while reliable, alternatives are preferred to mitigate the randomness in renewable energy generation and provide sufficient power reserve capacities.

Deployment of a battery energy storage system (BESS) is one viable solution to smooth out the fluctuations of the renewable energy generation. Specifically, BESSs help reduce the operational cost by being charged with surplus renewable energy and/or during periods of low electricity price and be then discharged during renewable energy deficit and/or periods of peak electricity price. On the other hand, recent studies have shown that only a single application of a BESS does not justify its high upfront investment cost [3]. Thus, the so-called "co-optimization" of the usage of a BESS, which utilizes it for another concurrent application, such as frequency regulation, has become appealing [5]. Although BESSs help address supply-demand power imbalance of the stochastic renewable energy generation and also provide power reserve capacity for frequency regulation service, it is not practical to rely solely on them, especially with high penetration of renewables. This is mainly due to their limited capacities, high upfront costs, degradation due to frequent charging/discharging, etc.

Another viable solution to address the supply-demand power imbalance and also achieve further energy cost saving is by enabling demand-responsive (DR) loads and adjusting users' power consumption so as to match it with supply power received from the grid and/or renewable energy generators as closely as possible. DR loads are specifically highly effective in commercial buildings, since their electrical energy consumption is much higher than residential buildings (e.g., based on Singapore energy statistics reported by energy market authority (EMA), around 36% and 15% of the total electricity consumption in 2016 was related to commercial and residential buildings, respectively [4]). Among all potential appliances and energy consumers in commercial buildings whose energy consumption can be varied flexibly over time, heating, ventilation, and air conditioning (HVAC) systems are of significant importance. This is due to the fact that the speed and power consumption of modern fans in commercial buildings can be varied quickly and almost continuously through their existing variable frequency drives (VFDs) to act as primary or

secondary frequency regulation services (s
without requiring any additional hardwa
hence, making them ideal for frequency re

Overall, both BESSs and fans of smar
highly effective for energy cost saving a
ulation. However, it is crucial to come
that efficiently coordinates both BESSs ar
achieve a cost-effective solution, but also
reserve capacities to restore the frequency
Hence, this paper studies the mathematica
and joint optimization of a BESS and fans
and frequency regulation, which is new an
knowledge, has not been rigorously studie

Energy management for systems with re
BESS integration has been widely investiga
e.g. see [6], [7] and references therein. U
frequency regulation in response to grid's
in e.g. [5], [8]–[11], where [5], [10], [11]
cost efficiency of the BESS by considering its degradation cost. On the other hand, utilizing DR capability of fans for energy cost saving by adjusting their power consumption flexibly over time subject to user comfort constraints was studied in [12]. Furthermore, [13], [14] investigated the effectiveness and control of fans in response to frequency regulation signals received from the grid.

In contrast to the aforementioned works, where a BESS serves a single application and it is challenging to justify its high upfront investment, this paper mathematically models the BESS such that it is utilized in day-ahead energy management to reduce the cost, while reserving a proportion of its capacity to respond to grid's over/under-frequency. To further reduce the operational cost and also provide a larger reserve capacity, we quantify the power reserve capacity of the fans such that users' comfort is met. Next, a novel joint optimization framework that exploits the advantages of both BESS and fans is developed to achieve energy cost saving while providing reserve service for the grid. Simulation results show that the joint optimization of the BESS and fans achieves a higher cost saving compared to existing benchmarks, by utilizing both the flexibility of the fans' energy consumption and enabling charging/discharging to/from the BESS.

II. System Model

We consider a building with a BESS, fixed load (e.g., lighting) that should be instantly satisfied upon request, and also fans of the HVAC system that consume energy to operate flexibly, subject to operational constraints, as shown in Fig. 1. A time-slotted system with slot index n, $1 \leq n \leq N$ is considered, where N denotes the total energy scheduling time slots. The duration of each time slot is denoted by $\tilde{n}$.

In the following, we discuss the system model in detail.

1) Battery Energy Storage System (BESS): The power charged (discharged) to (from) the BESS at time slot n is denoted by $C_n \geq 0$ ($D_n \geq 0$). A practical BESS experiences energy losses in charging and discharging, which are captured by the charging and discharging efficiency parameters, denoted

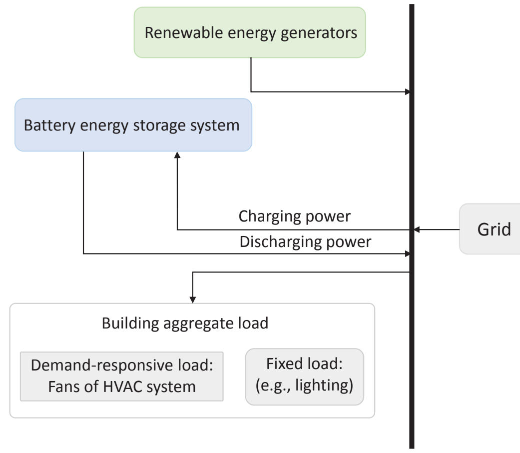

Fig. 1. System model: a grid-connected building comprising of DR fans, BESS, and renewable energy generators.

by $0 < \dot{\alpha} < 1$ and $0 < \ddot{\alpha} < 1$, respectively. Denote the state of the BESS at the beginning of each time slot n as $S_n \geq 0$. The dynamics of the BESS can then be derived as follows:

$$S_{n+1} = S_n + \dot{\alpha} C_n - 1/\ddot{\alpha} D_n, \ \forall n \in \mathcal{N}. \tag{1}$$

Furthermore, a BESS has a finite capacity and it cannot be fully discharged. We denote the maximum energy capacity as $\overline{S} \geq 0$ and the minimum energy level as $\underline{S} \geq 0$, to avoid deep discharging. Thus, we have

$$\underline{S} \leq S_n \leq \overline{S}, \ \forall n \in \mathcal{N}, \tag{2}$$

where $\underline{S} \leq S_1 \leq \overline{S}$ is assumed by default.

Cycling conditions such as the number of frequent charging and discharging, and the cycle depth of discharge highly affect the battery capacity over time and its degradation. Denote $b(C_n, D_n)$ as the operating cost of the BESS. As for Li-ion batteries, $b(C_n, D_n)$ can be approximated by linear or piece-wise linear functions [11].

2) HVAC System and Fan models: We consider an HVAC system in a modern commercial building, also named variable air volume (VAV) system, as shown in Fig. 2. We briefly discuss the operation of the VAV in the sequel. Readers are referred to [13] for more details.

The air handing unit (AHU) circulates the return air from building zones and mixes it with fresh outdoor air, where the mixed air is then directed to the cooling coil through the supply fans to become cool and reduce its humidity. Each zone has a controller that adjusts the mass flow rate such that the temperature of the zone tracks a target temperature. When the zone temperature deviates from its target, the change is measured by a sensor and the fan controller changes the AHU supply fan speed accordingly, through a control command to the VFD. The VFD is a programmable fast-response power electronic device, which varies the fan motor speed by changing the motor input frequency.

Denote $\underline{V} \leq V_n \leq \overline{V}$ as the speed of the fan at time slot n, where $\underline{V}$ and $\overline{V}$ denote the minimum and maximum allowable speeds, respectively. The aggregate power consumption of the fans is given by[1]

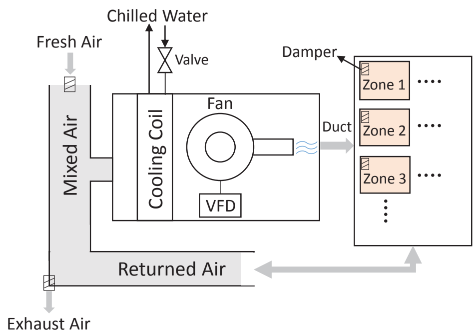

Fig. 2. Schematic of a HVAC system in a typical commercial building.

$$F_n = a_1 V_n^3, n \in \mathcal{N}, \tag{3}$$

where $a_1 > 0$ is a given constant. Due to the fan speed constraints, the energy consumption of the fans also satisfies $\underline{F} \leq F_n \leq \overline{F}$, where $\underline{F} = a_1 \underline{V}^3$ ($\overline{F} = a_1 \overline{V}^3$). The aggregate supply air flow is given by

$$M_n = a_2 V_n, n \in \mathcal{N}, \tag{4}$$

where $a_2 > 0$ is a given constant. From (3) and (4), the supply air flow is expressed as a function of the fan power consumption as follows

$$M_n = a_3 F_n^{1/3}, \tag{5}$$

where $a_3 = a_2 / a_1^{1/3}$.

3) Aggregate Building Thermal Model: We consider the thermal model of the building based on the aggregate building temperature, which can be considered as the *average* temperature of all zones. The lumped thermal model of the building is given by [13], [15]

$$C\dot{T} = \frac{1}{R}(T_{o,n} - T_n) + c_a M_n (T_s - T_n) + Q_n, n \in \mathcal{N}, \tag{6}$$

where $\dot{T}$ is the derivative of the temperature with respect to time n, C and R are the thermal capacitance and thermal resistance of the building, respectively, $T_{o,n}$ is the outdoor temperature at time n, c_a is the specific heat of air, T_s is the air temperature of AHU, and finally, Q_n is the external disturbance. Using the finite-difference methods, the lumped thermal model of the building can be expressed in the discrete form over time slots n with intervals $\tilde{n}$, as follows [15]

$$C\frac{(T_{n+1} - T_n)}{\tilde{n}} = \frac{1}{R}(T_{o,n} - T_n) + c_a M_n (T_s - T_n) + Q_n, n \in \mathcal{N}. \tag{7}$$

From (5) and (7), the dynamic of the room temperature at each time slot n can be derived recursively from the temperature of the previous time slot, the power consumption of the fans, and other environmental effects. We thus have

$$T_{n+1} = \omega_1 T_n + \omega_3 F_n^{1/3}(T_s - T_n) + \omega_2 T_{o,n} + \frac{\tilde{n}}{C} Q_n, n \in \mathcal{N}, \tag{8}$$

[1]The derived results can be extended to a more complex model with individual zonal controls, in a way similar to that presented in [13].

where $\omega_1 = 1 - \omega_2$, $\omega_2 = \frac{\tilde{n}}{RC}$, $\omega_3 = \frac{\tilde{n} c_a a_3}{C}$.

To ensure the comfort of the building occupants, the temperature of the room should vary within a desirable range:

$$|T_n - T_{tr,n}| \leq \tilde{T}, \forall n \in \mathcal{N}, \tag{9}$$

where $T_{tr,n}$ is the target temperature for time slot n and $\tilde{T}$ is the admissible temperature deviation, both are to be set by the building operator.

4) Energy Conservation Constraints: Denote $RE_n \geq 0$ and $L_n \geq 0$ as the renewable energy generation and the aggregate fixed load (excluding fans' power demand) of the building at time slot n. We define $\Delta_n = RE_n - L_n$ as the *net energy profile*. Note that Δ_n is positive in case of renewable energy surplus, while becomes negative in case of renewable energy deficit. Δ_n's are generally stochastic due to the random characteristics of the renewable energy generation and load, but both can be predicated with finite errors in practice, using the existing forecasting techniques. However, herein, we assume that Δ_n's are known prior to the scheduling. Denote $G_n \geq 0$ as the power purchased from the grid at time n. To ensure that the energy requirements of loads and fans are fully satisfied via the grid and/or BESS, we have

$$G_n - C_n + D_n - F_n + \Delta_n \geq 0, n \in \mathcal{N}. \tag{10}$$

We consider a linear cost model for purchasing power from the grid, where the building pays a per-unit time-variant price of $\lambda_{g,n}$ to the grid. The total energy cost is thus given by

$$f(\{G_n\}) = \sum_{n=1}^{N} \lambda_{g,n} G_n. \tag{11}$$

5) Regulation Capacities: Denote $R_{b,n}$ and $R_{f,n}$ as the hourly regulation power capacities provided by the BESS and fans for both over and under frequency conditions, respectively. We consider symmetrical frequency regulation capacities, providing the same capacities in both over and under frequency conditions. In practice, frequency regulation market participants need to provide a minimum reserve capacity, denoted by $R_{\min}$, to be eligible for frequency regulation service provider [16]. On the other hand, the BESS and fans cannot provide regulation capacities beyond given thresholds due to their practical constraints. We thus have the following constraints for the reserve capacities of the BESS and fans:

$$R_{\min,b} \leq R_{b,n} \leq \overline{S} - \underline{S}, n \in \mathcal{N} \tag{12}$$

$$R_{\min,f} \leq R_{f,n} \leq \overline{F} - \underline{F}, n \in \mathcal{N}, \tag{13}$$

where $R_{\min,b}$ and $R_{\min,f}$ are the minimum reserve capacities provided by the BESS and fans, respectively, with $R_{\min} = R_{\min,b} + R_{\min,f}$.

It is assumed that the grid operator pays a per-unit reservation fee of $\lambda_{res} > 0$ for providing the standby capacity for frequency regulation. The total revenue gained from providing frequency regulation service is then given by

$$g(\{R_{b,n}, R_{f,n}\}) = \sum_{n=1}^{N} \lambda_{res}(R_{b,n} + R_{f,n}). \tag{14}$$

6) Total Energy Cost of the Building: The objective is to minimize the total energy cost of the building, resulting from its purchase from the grid and the degradation cost of the BESS, minus the revenue derived from power reserve capacity allocation for frequency regulation service. The total energy cost of the system is thus defined as follows:

$$y(\mathcal{X}) = f(\{G_n\}) + \sum_{n=1}^{N} b(C_n, D_n) - g(\{R_{b,n}, R_{f,n}\}), \quad (15)$$

where $\mathcal{X} \triangleq \{G_n \geq 0, 0 \leq C_n \leq \overline{C}, 0 \leq D_n \leq \overline{D}, \underline{F} \leq F_n \leq \overline{F}, T_n \geq 0, R_{\min,b} \leq R_{b,n} \leq \overline{S} - S_1, R_{\min,f} \leq R_{f,n} \leq \overline{F} - \underline{F}, \forall n \in \mathcal{N}\}$.

III. Problem Formulation

In this section, we formulate and solve the day-ahead cost minimization problem to derive the optimized regulation capacities provided by both DR fans and BESS, as well as the optimized day-ahead energy management solution as follows:

$$\text{(P1)}: \min_{\mathcal{X}} \; y(\mathcal{X})$$

$$\text{s.t.}\; S_n + \dot{\alpha} C_n - 1/\ddot{\alpha} D_n \leq \overline{S} - \dot{\alpha} R_{b,n}, \forall n \in \mathcal{N} \quad (16)$$

$$S_n + \dot{\alpha} C_n - 1/\ddot{\alpha} D_n \geq \underline{S} + R_{b,n}/\ddot{\alpha}, \forall n \in \mathcal{N} \quad (17)$$

$$R_{b,n} \leq \min\{\overline{C} - C_n, \overline{D} - D_n\}, \forall n \in \mathcal{N} \quad (18)$$

$$R_{f,n} \leq \min\{F_n - \underline{F}, \overline{F} - F_n\}, \forall n \in \mathcal{N} \quad (19)$$

$$T_{n+1} = \omega_1 T_n + \omega_3 F_n^{1/3}(T_s - T_n) + \omega_2 T_{o,n} + \frac{\tilde{n}}{C} Q_n, \forall n \in \mathcal{N} \quad (20)$$

$$|T_n - T_{tr,n}| \leq \tilde{T}, \forall n \in \mathcal{N} \quad (21)$$

$$G_n - C_n + D_n - F_n + \Delta_n \geq 0, \forall n \in \mathcal{N}, \quad (22)$$

with $\mathcal{X} = \{G_n \geq 0, 0 \leq C_n \leq \overline{C}, 0 \leq D_n \leq \overline{D}, \underline{F} \leq F_n \leq \overline{F}, T_n \geq 0, R_{\min,b} \leq R_{b,n} \leq \overline{S} - S_1, R_{\min,f} \leq R_{f,n} \leq \overline{F} - \underline{F}, \forall n \in \mathcal{N}\}$. The constraints in (16)-(17) ensure that the capacity allocated for frequency regulation cannot be used for the operational day-ahead charging/discharging. The constraints in (18) ensure that BESS reserve capacity satisfies charging/discharging rates. The constraints in (19) are for fans' power reserve capacity. The constraints in (20)-(21) are due to building temperature dynamics and limit deviations from the target temperature to ensure occupants' comfort. Finally, the constraints in (22) ensure that fixed load demand is always met.

Note that the optimization problem in (P1) is non-convex due to the nonlinear terms in (20). Herein, we develop a sequential convex programming (SCP) based algorithm which obtains a local optima for the non-convex program by solving a sequence of degenerated convex programs [17], [18] . We denote $\mathcal{X}^* \triangleq \{G_n^*, C_n^*, D_n^*, F_n^*, T_n^*, R_{b,n}^*, R_{f,n}^*, \forall n \in \mathcal{N}\}$ as the (locally) optimal solution to (P1).

IV. Simulation Results

To evaluate the effectiveness of joint optimization of the proposed BESS and fans, we consider a commercial building which integrates renewable energy supplies (both solar and wind), a BESS, and multiple fans with VFD controllers. The scheduling horizon is set as one day with $N = 24$ (i.e., with a uniform slot duration of $\tilde{n} = 1$ hour). Energy profiles of load and renewable energy generation of the building are shown in Fig. 3-a [19], [20]. The wholesale electricity price to purchase from the grid and the reservation fee paid by the grid due to the provision of reserve capacity are shown in Figs. 3-b and 3-c, respectively [16], [21]. Outdoor temperature, target temperature, and external disturbances are all shown in Figs. 3-d to 3-f, respectively. Other thermal specifications of the system are listed in Table I. The BESS parameters are shown in Table II, and we set $b_n = 0.0073$ \$/kW, $\forall n$. Finally, we set $R_{\min,b} = 20$ kW and $R_{\min,f} = 0$, which ensures that the system provides a minimum overall reserve capacity of $R_{\min} = 20$ kW to be eligible for the regulation service.

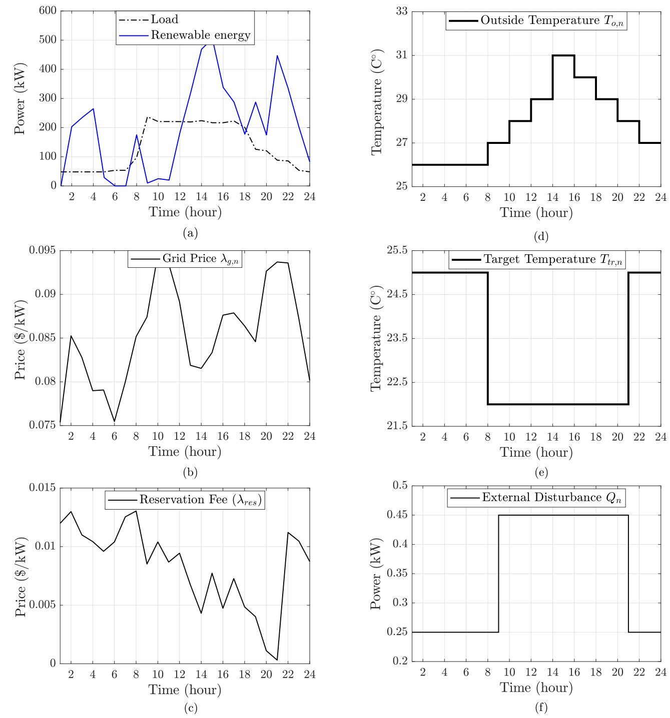

Fig. 3. System characteristics over the time horizon of 24 hours: (a) Aggregate load and renewable energy profiles, (b) Wholesale electricity price, (c) Reservation fee paid by the grid to stand-by resources, (d) Outdoor temperature, (e) Indoor target temperature, and (f) External disturbances.

TABLE I
THERMAL PARAMETERS

C (kJ/K)	c_a (kJ/K)	R (K/kW)	a_3 (kW/(kg/s)^3)	T_s (C°)
1000	1	25	0.35	12.8

TABLE II
PARAMETERS OF THE BESS

$\underline{S}$ (kWh)	$\overline{S}$ (kWh)	$\overline{C}$ (kW)	$\overline{D}$ (kW)	$\dot{\alpha}$	$\ddot{\alpha}$
25	250	50	50	0.95	0.95

A. Benchmarking

In this subsection, we highlight the effectiveness of the joint optimization of the BESS and fans in reducing the total energy cost and providing power reserve capacity for frequency regulation service, compared to conventional setups, without such joint optimization.

TABLE III
BENCHMARK COMPARISON FOR THE TOTAL ENERGY COSTS

Case	Joint BESS & Fans	Only BES, non-DR fans	Only DR Fans, no BESS
Total energy cost $y(\mathcal{X}^*)$ ($)	60.9	69.4	75.8

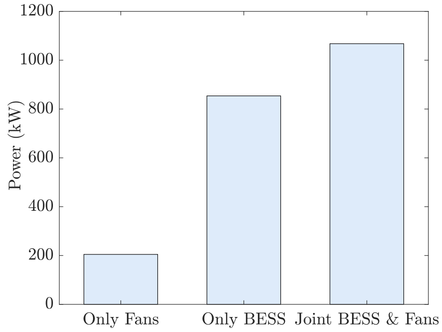

Fig. 4. Benchmark comparison for the provision of power reserve capacity.

1) Total Energy Cost Reduction of the Building: To provide benchmark comparison for the total energy cost resulting from the joint optimization of the BESS and DR fans, we consider two cases of "only BESS, non-DR fan", where the DR capability of fans is disabled (no temperature variations from the target values are allowed, i.e. $\tilde{T} = 0$), and "only DR fans, no BESS", where BESS capacity is set to zero ($\overline{S} = 0$). Table III shows the total energy cost over one day for the three different setups. It can be verified that our proposed case of joint BESS and fans achieves the lowest total energy cost, i.e., around 14% and 25% more cost saving compared to the two conventional cases of "only BESS, non-DR fan" and "only DR fans, no BESS", respectively, by utilizing both the flexibility of the fans' energy consumption and enabling charging/discharging to/from the BESS.

2) Provision of Higher Power Reserve Capacity: Fig. 4 shows the total reserve capacities for the three different setups of "only fans" with $R_{b,n} = 0$, $\forall n$, "only BESS" with $R_{f,n} = 0$, $\forall n$, and "joint BESS and fans" with both BESS and fans enabled for frequency regulation. Note that in each of the two cases of only fans and only BESS, both fans and BESS are available, but only one is enabled to provide power reserve capacity. It is observed that the case of joint BESS and fans provides a significantly higher power reserve capacity over the other two cases (and hence the resulting revenue is higher). This is expected, since the BESS and fans have different characteristics in the provision of power reserve and can complement each other. This can be verified from Fig. 5, where at time slots that the BESS provides the minimum amount of power reserve capacity, e.g., time slots 2 to 5, the fans are available to compensate, while the opposite is true for time slots 5 to 8.

3) Provision of the Same Power Reserve Capacity with a Smaller BESS Capacity Requirement: The total power reserve capacity resulting from "joint BESS and fans" setup and "only BESS" setup over the maximum capacity of the BESS are

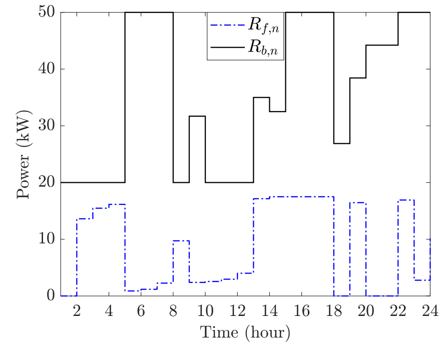

Fig. 5. Power reserve capacity provided by the BESS and fans in the joint BESS and fans setup.

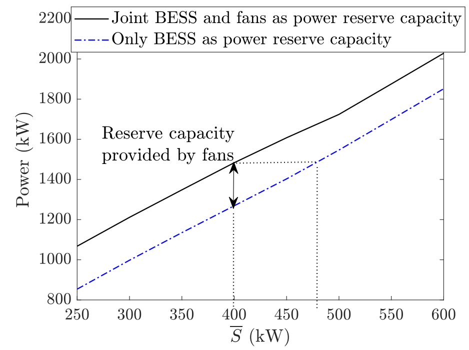

Fig. 6. Power reserve capacity vs. the maximum available BESS capacity.

shown in Fig. 6. It is observed that the total power reserve capacity in both cases increases over $\overline{S}$, which is because more potential capacities are available for regulation service. Furthermore, it is shown that the proposed case of joint BESS and fans achieves the same total power reserve capacity target with a smaller BESS capacity as compared to the case of only BESS. For instance, to achieve the total power reserve capacity of 1480 kW, $\overline{S} = 400$ kW is set in the case of joint BESS and fans. However, for the case of only BESS, we need to set $\overline{S} = 480$ kW. This shows that our proposed strategy significantly reduces the required BESS capacity by enabling the capability of fans to provide reserve capacity.

B. Feasibility

By considering the case of joint BESS and fans in providing frequency regulation service, we derive the optimized day-ahead charging and discharging values $\{C_n^*, D_n^*\}_{n=1}^N$ (by solving (P1)) as shown in Fig. 7. Given $\{C_n^*, D_n^*\}_{n=1}^N$, the optimized day-ahead states of the BESS, denoted by S_n^*, are illustrated in Fig. 8. From Fig. 7 and Fig. 8, it is observed that the optimized BESS power reserve capacity $\{R_b^*\}$ satisfies the minimum power requirement of $R_{\min,b} = 20$ kW. BESS power reserve capacity is mainly available when the state of the BESS is neither too high nor too low and meanwhile its charging and discharging rates are less than the maximum values. Finally, Fig. 9 shows that the optimized temperature of the room varies within 1.5 C° of the target temperature, which

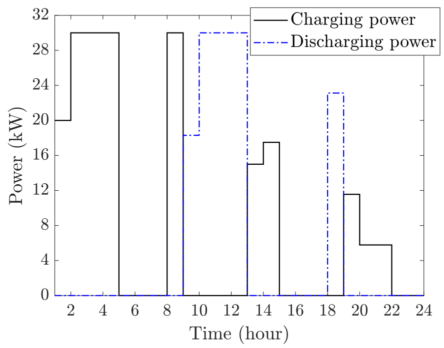

Fig. 7. Optimized day-ahead BESS charging and discharging powers.

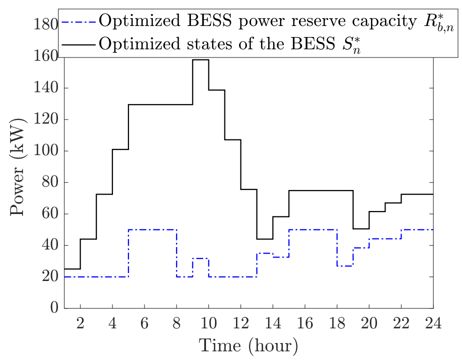

Fig. 8. Optimized states of the BESS and corresponding reserve capacities.

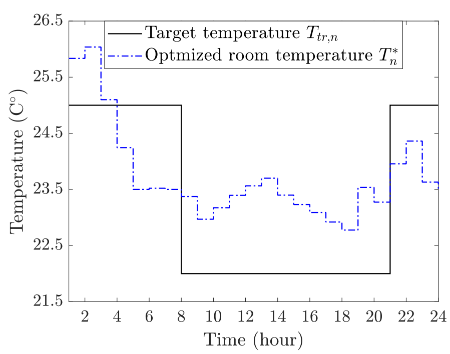

Fig. 9. Optimized temperatures of the room.

ensures that fans provide sufficient power reserve capacity while the temperature comfort constraints are all met.

V. Conclusions and Future Works

This paper proposes a novel strategy for the joint optimization of a BESS and DR fans to achieve a lower total energy cost and also the optimized power reserve capacities provided by both BESS and fans for frequency regulation service. Our proposed strategy is applicable to any existing BESS integrated systems, in which the BESS is not being used efficiently, e.g. in emergency power system applications. The participation of the BESS together with joint optimization of the DR fans in frequency regulation service enables the BESS owner to gain higher revenue and reduce the fixed asset depreciation costs of the BESS. For systems in the planning phase, our proposed strategy on the joint optimization of BESS and DR fans improves and justifies the cost-effectiveness of BESS deployment and accelerates the roadmap towards sustainability. Given the optimized power reserve capacities, our future work is to develop a strategy that enables the BESS and fans integrated system to respond to frequency regulation signals in real time, by optimizing both BESS and fans, while committing to the derived optimized day-ahead values. By doing so, both energy cost saving and frequency regulation service goals, which are of significant importance for the power system, can be achieved.

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