Optimal dispatch strategy for building aggregators to fully utilize the energy flexibilities

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Abstract. Well-managed demand-side flexibility can effectively alleviate the pressure on the reliability of the power system and the advanced development of smart grid technologies creates win-win opportunities for the power system operators and demand-side users. The building sector, as one of the largest consumers of electricity, has great flexibility potential through smart load control and natural thermal mass storage. However, few studies have investigated the potential contribution of buildings in providing multiple flexibility services without sacrificing the occupants' comforts. Another major hurdle to utilizing the building energy flexibility is that individual buildings usually cannot reach a sufficient size to bid the flexibility services in the electricity market. Therefore, this paper proposes an optimal dispatch strategy for building clusters using mixed-integer non-linear programming (MINLP) to aggregate and utilize full-scale energy flexibilities of variable controllable loads, the passive thermal mass storage and active electrical storage systems. The building cluster consisting of five commercial buildings is selected in the case study to test the proposed strategy and analyze the practical relevance based on a real-life electricity market. Results show that the proposed dispatch strategy reduces the electricity costs of the building cluster by 11.6% from multiple revenue streams, including energy arbitrage, regulation service and operating reserve service. Active electrical storage systems can increase revenues by 2.3 times and the unlocked flexibility of building thermal and lighting loads can achieve 152 $ daily revenues. This study addresses the issue that the energy flexibility of individual buildings is too small to bid flexibility services, and the findings may stimulate the investment of the distributed storage system at the aggregated level, as the building aggregator is a promising business model in future flexibility markets.

Keywords. Demand-side flexibility, building aggregator, bidding strategy, multiple flexibility services.
DOI: https://doi.org/10.34641/clima.2022.414

Abbreviations and Nomenclature.

P^E	Total purchased energy	A_{bui}	Effective building surface
π^E	Energy price	Cap_{min}	Minimum bid capacity
π^{Rs}	Reserve service price	SOC_{ES}	State of charge of the electrical storage
π^{Rg}	Regulation service price	COP	Coefficient of performance
ΔQ_{ch}	Cooling supply alteration	LO	Lowest operating limit
β_L	Acceptable level of lighting regulation	ES	Electrical storage
γ_L	Acceptable level of lighting reserve	Rev	Revenues from ancillary services
T_i	Indoor temperature	lig	Lighting system
T_o	Outdoor temperature	k	Time slot k
$R_{bui,o}$	Outer thermal mass resistance	i	Building cluster
$R_{bui,i}$	Inner thermal mass resistance		
C_{bui}	Thermal capacitance of per square		

1. Introduction

Renewable generation is increasingly integrated into the modern power system to achieve energy transitions and environmental targets (e.g., carbon neutrality), while it raises pressure on the reliability of the power grid due to the uncertain and intermittent nature of solar and wind power [1]. Well-managed demand-side flexibility can effectively alleviate the pressure and the advanced development of smart grid technologies creates win-win opportunities for the power system operators and demand-side users. Multiple electricity services are introduced in the electricity markets for economic energy dispatch and short-term power balancing, e.g., energy arbitrage and ancillary services. The balancing services in the wholesale electricity market are gradually open to the direct demand-side participants who have great flexibility potential to provide such services. For example, the integration of electric vehicles into the grid cannot be only considered as the charging loads, but can also be the flexibility aggregator to bid the flexibility services in the electricity markets [2, 3]. Besides microgrids and virtual power plants consisting of multiple loads, storage resources and distributed generation, demand-side aggregator [4] is also an emerging business model in the market trading, which can effectively help demand-side participants avoid the spike price in the wholesale markets [5].

The building sector, as one of the largest consumers of electricity, has great flexibility potential through smart load control and natural thermal mass storage. Numerous studies have investigated the demand response potential of both individual buildings and the building clusters, on load shifting [6, 7], grid frequency regulation [8] and power reserve capacity [9]. However, few studies have investigated the potential contribution of buildings in providing multiple flexibility services and on how to optimally allocate the flexibility capacity to different flexibility services without sacrificing the occupants' comforts [10]. Moreover, in some real-life electricity markets, there usually exists the requirement of the minimum bid capacity for flexibility services. For example, the minimum bid capacity for ancillary services in PJM (Pennsylvania, New Jersey, and Maryland) and CAISO (the California Independent System Operator) markets are 100 kW and 500 kW, respectively. Individual buildings usually cannot reach a sufficient size to bid the flexibility services in the electricity market, which is the major hurdle to be overcome when utilizing the building energy flexibility. The business model "building aggregator" can effectively address this issue by aggregating a cluster of buildings and optimally dispatch their flexibility capacities.

Therefore, this paper proposes an optimal dispatch strategy for building aggregators to fully utilize the building energy flexibilities using mixed-integer non-linear programming (MINLP). The coordinated control of multiple flexibility resources, including variable controllable loads, the passive thermal mass storage and active electrical storage systems, is optimized to maximize the economic benefits of building clusters considering multiple revenue streams in the electricity markets. A case study is conducted to test the proposed strategy and analyse the practical relevance.

2. Methods

2.1 Multiple flexibility services in the electricity markets

As shown in Fig. 1, there are three stages in the planning and scheduling of the power system, including system balancing, energy-economic dispatch and capacity planning. Therefore, multiple electricity products are introduced in the electricity markets, where frequency regulation and operating reserve are two ancillary services for power balancing requiring the service provider to respond within a few seconds or minutes. Dynamic hourly and sub-hourly energy tariffs are scheduled which stimulate the market participants to optimize the energy dispatch. It is reasonable to assume that the building energy flexibilities can be transformed to bid the energy and capacity bands in joint energy and ancillary services markets, as multiple flexibility resources enable the building to respond at different time scales. In this paper, the day-ahead joint market referring to CAISO (the California Independent System Operator) is considered where energy trading and ancillary services are co-optimized at the same time.

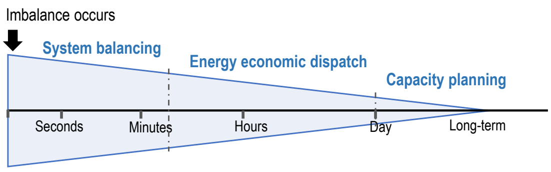

Fig. 1 - Three stages of power system planning and scheduling.

2.2 Bi-level optimal dispatch strategy of the building aggregator

In the building aggregator model as shown in Fig. 2, all individual buildings interface with aggregators through building energy management systems (BEMS) and send the storage information and flexibility quantification results of variable loads. After that, the aggregator can allocate the flexibility capacity to different flexibility services to maximize the profits or minimize the electricity costs according to the service prices. In this paper, the aggregator is assumed as the price-taker.

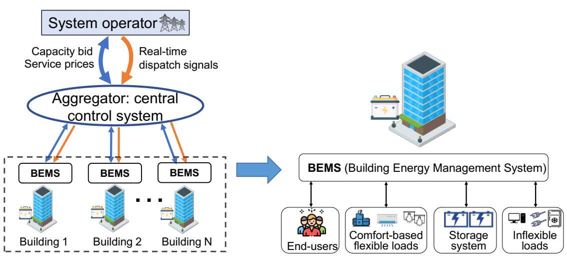

Fig. 2 - Structure of the aggregator control system and the building energy management system.

The dispatch optimization of the aggregator can be formulated as a cost minimization problem as shown in Eq. (1), equal to the energy cost minus the revenues from regulation and reserve services. The constraints are presented by formulation (2)-(12).

$$min\ \ Cost = \sum_{k\in T}(\pi_k^E P_k^E - Rev_{reg,k} - Rev_{res,k}) \quad (1)$$

$$P_k^E = \sum_{i\in N}\left(P_{ES,i,k}^E + P_{lig,i,k}^E + P_{HVAC,i,k}^E + P_{others,i,k}^E\right) \quad (2)$$

$$Cap_k^{Rs} = \sum_{i\in N}(Cap_{ES,i,k}^{Rs} + Cap_{lig,i,k}^{Rs} + Cap_{HVAC,i,k}^{Rs}) \quad (3)$$

$$Cap_k^{Rg} = \sum_{i\in N}(Cap_{ES,i,k}^{Rg} + Cap_{lig,i,k}^{Rg} + Cap_{HVAC,i,k}^{Rg}) \quad (4)$$

$$Rev_{reg,k} = \begin{cases} 0 & Cap_k^{Rg} < Cap_{min}^{Rg} \\ \pi_k^{Rg} Cap_k^{Rg} & Cap_k^{Rg} \geq Cap_{min}^{Rg} \end{cases} \quad (5)$$

$$Rev_{res,k} = \begin{cases} 0 & Cap_k^{Rs} < Cap_{min}^{Rs} \\ \pi_k^{Rs} Cap_k^{Rs} & Cap_k^{Rs} \geq Cap_{min}^{Rs} \end{cases} \quad (6)$$

$$-P_{ES,i,k}^{\vee} - Cap_{ES,i,k}^{Rs} - Cap_{ES,i,k}^{Rg} \geq -P_{ES,i,rated} \quad (7)$$

$$P_{ES,i,k}^{\wedge} + Cap_{ES,i,t}^{Rg} \leq P_{ES,i,rated} \quad (8)$$

$$SOC_{ES,i,k+1} = SOC_{ES,i,k} + \frac{\eta_i P_{ES,i,k}^{\wedge} - P_{ES,i,k}^{\vee}/\eta_i}{E_{ES,i,rated}} \quad (9)$$

$$SOC_{ES,i,k,max} = SOC_{ES,i,k} + Cap_{ES,i,k}^{Rg} * 0.5/E_{ES,i,rated} \quad (10)$$

$$SOC_{ES,i,k,min} = SOC_{ES,i,k} - \frac{Cap_{ES,i,k}^{Rg} * 0.5 + Cap_{ES,i,k}^{Rs}}{E_{ES,i,rated}} \quad (11)$$

$$\underline{SOC}_{ES,i} \leq SOC_{ES,i,k}, SOC_{ES,i,k,max}, SOC_{ES,i,k,min} \leq \overline{SOC}_{ES,i} \quad (12)$$

At the building level, the model-based flexibility quantification method is used to evaluate the flexibility capacity of the comfort-based loads including thermal and lighting loads, as presented by formulation (13)-(21) [10]. Where L is the horizontal illuminance on the working plane. P is the light power input. LE is the luminous efficacy of each lamp (80 am/W). UF is the utilization factor (0.4~0.6). MF is the maintenance factor (Good condition: 0.7). A simplified building thermal storage model (RC model) is used to predict the alternation of building cooling demand when utilizing the building thermal mass as the flexibility resource.

$$L_{w,k} = \frac{LE \times UF \times MF \times (P_{lig,k}^E - Cap_{lig,k}^{Rg} - Cap_{lig,k}^{Rs})}{Area} \quad (13)$$

$$L_{min} \leq L_{w,k} \leq L_{max} \quad (14)$$

$$Cap_{lig,k}^{Rg} \leq \beta_L P_{lig,k}^E \quad (15)$$

$$Cap_{lig,k}^{Rs} \leq \gamma_L P_{lig,k}^E \quad (16)$$

$$\Delta Q_{ch,k} = \frac{T_{opt,k} - T_{base,k}}{R_{bui,o} + R_{bui,i}} \times \left(1 + \frac{R_{bui,o}}{R_{bui,i}} \times e^{-\frac{t}{\tau}}\right) \times A_{bui} \quad (17)$$

$$\tau = \frac{R_{bui,o} \times R_{bui,i}}{R_{bui,o} + R_{bui,i}} \times C_{bui} \quad (18)$$

$$\Delta P_{Ch,k}^E = \Delta Q_{ch,k}/COP \quad (19)$$

$$Cap_{Ch,k}^{Rg} \leq min\ (P_{Ch,rated} - P_{Ch,k}^E, P_{Ch,k}^E - P_{Ch,LO}, \Delta P_{Ch,k}^E) \quad (20)$$

$$Cap_{Ch,k}^{Rs} = min\ (P_{Ch,k}^E - P_{Ch,LO}, \Delta P_{Ch,k}^E) - Cap_{Ch,k}^{Rg} \quad (21)$$

3. Description of the case study

The building cluster consisting of five 40-floor commercial buildings (1*low-weighted, 3*middle-weighted, 1*high-weighted) is selected in the case study to test the proposed strategy and analyse the practical relevance based on the real-life electricity market. All individual buildings are equipped with an active electrical storage system (224 kWh, 80 kW). Fig. 3 (a) shows the time-varying prices of different market services including the energy, reserve, and regulation (sum of up and down) services. The minimum bid capacity for regulation and reserve services is 500 kW. Table. 1 shows the RC parameters of the building clusters. The weather data is adopted from available Hong Kong TMY (typical meteorological year) data, as shown in Fig. 3 (b). The occupied period is 8:00-20:00 with a constant indoor temperature setting of 24°C and humidity of 60% RH in the baseline case. The lighting density is assumed to be 15W/ m2 following the given baseline schedules. In the flexibility quantification, the maximum allowed indoor temperature increase is 2K and the minimum indoor illuminance is 300 lux.

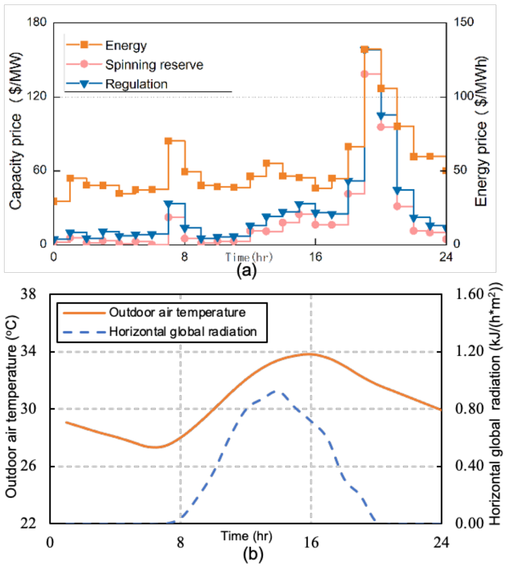

Fig. 3 – (a) Hourly energy prices and ancillary service revenues from CAISO; (b) Outdoor weather on the test day.

Tab. 1 - RC parameters of building thermal model [11].

Building type	Low weighted	Middle weighted	High weighted
Cbui (j/m2.k)	248621	467878	696082
Rbui,o (m2.k/W)	0.9236	0.6551	0.5266
Rbui,i (m2.k/W)	0.2133	0.1477	0.1134
Rbui (m2.k/W)	0.1733	0.1205	0.0933

4. Results

The optimization target of the dispatch strategy is programmed as the mixed-integer non-linear problem via YALMIP [12], and solved with CPLEX solver using a computer with an eight-core Intel Core i7 CPU.

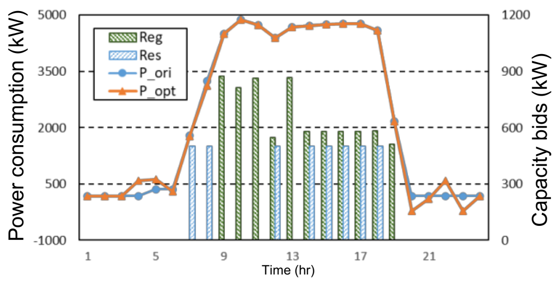

Fig. 4 - The optimal bidding result of the building aggregator.

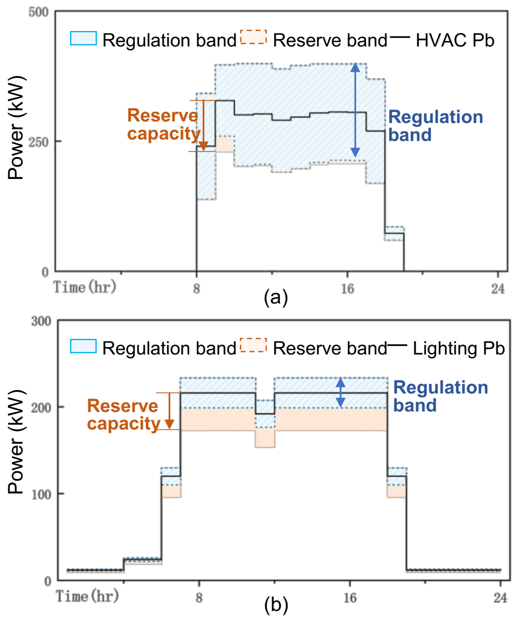

Fig. 5 - The power baseline and flexibility capacity of (a) the HVAC system and (b) the lighting system of the high-weighted building.

Tab.2 - Revenues of the building aggregator from different flexibility services.

Multiple services	Cost saving
Energy arbitrage income($)	33.6
Regulation revenue income($)	220.8
Reserve revenue income($)	78.2
Total cost saving ($)	332.7 (11.6%↓)

Fig. 4 shows the optimal bidding results of the building aggregator during a 24-hour period. Fig. 5 shows an example of the hourly power baseline and flexibility capacities (i.e., regulation band and reserve capacity) of the high-weighted building. If individually optimizing the dispatch of each building, only 80.2 $ daily cost saving can be achieved in total from load shifting by the storage system, since the flexibility capacity of individual buildings is too small to bid ancillary services. Through the coordinated dispatch of the active storage systems from aggregator central control systems, the flexibility of building thermal and lighting loads can be utilized to provide regulation and reserve services. The financial results are presented in Table.

2. Results show that the proposed dispatch strategy reduces the electricity costs of the building cluster by 11.6% from multiple revenue streams, including energy arbitrage, regulation service and operating reserve service. Active electrical storage systems can increase revenues by 2.3 times and the unlocked flexibility of building thermal and lighting loads can achieve 152 $ daily revenues. The total cost saving can reach 332.7 $, in which the flexibility of comfort-based loads contributes to 45.7% of the revenues and the active storage systems contribute to 54.3%.

5. Conclusion

Aggregated control of multiple flexibility resources can maximize the economic benefits of building clusters by ensuring a minimum capacity and optimally allocating the capacity to multiple services in the electricity market. This study addresses the issue that the energy flexibility of individual buildings is too small to bid flexibility services, and the findings may stimulate the investment of the distributed storage system at the aggregated level, as the building aggregator is a promising business model in future flexibility markets. The main conclusions are as follows:

1) The model-based flexibility quantification method is effective to evaluate the flexibility capacity of the comfort-based loads of the building.
2) The building aggregator business model can maximize the economic benefits of building energy flexibilities by providing multiple qualified services in electricity markets. The total electricity costs can be reduced by 11.6%.
3) The centralized control of the storage systems can be an economic and effective measure to unlock the energy flexibilities of the comfort-based loads which contribute to 45.7% of the revenues.

6. Acknowledgement

The research presented in this paper is financially supported by a research grant under strategic focus area (SFA) scheme of the research institute of sustainable urban development (RISUD) in The Hong Kong Polytechnic University and a general research grant (152165/20E) of the Hong Kong Research Grant Council (RGC).

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