Day-ahead Optimal Scheduling for Cluster Smart Buildings Considering Power Sharing

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Abstract. With the deregulation of power industry and increasing penetration of distributed energy resources, the study on the optimal schedule of demand-side resource under the electricity market environment has attracted wide attention from academia and industry. In this study, a market-based operational framework for cluster smart buildings is proposed. On this basis, a day-ahead optimal scheduling strategy and model for cluster smart buildings considering the overall power balance and consumer preferences and behaviors is proposed. The smart building energy management system comprising photovoltaic, electric vehicles and thermostatic controllable loads aims to minimize the total energy procurement cost. And then, the numerical results indicate that the proposed scheduling model can achieve local power sharing in the smart community. Finally, the optimal scheduling results under consideration or no consideration of the transformer power limit are discussed.

1. Introduction

With the increasing penetration of distributed energy resources (DERs) and the rapid development of demand response technology, end-users consisting of temperature controllable loads (TCLs), electric vehicles (EVs), photovoltaic (PV) and fixed loads have ability to participate in the electricity markets. Through the incentive of market price signal, fully leveraging the flexibilities available from demand-side resource can bring economic benefits to the end-users and the grid while reducing carbon emissions [1 - 2].

Presently, many studies on the day-ahead scheduling strategy and model for demand-side end-users have been carried out [1, 3 - 6]. [1, 3] performed the joint optimal scheduling strategy for a smart building energy management system (EMS) considering the electrical and thermal constraints. [4 - 5] established a day-ahead scheduling model of microgrid with the aim of minimization of electricity cost, but did not consider the impact of users’ behaviors. In [6], an optimal scheduling model and strategy for multiple smart buildings with EVs, energy storage system and interruptible loads to participate in the wholesale electricity market was proposed.

In this study, under the market-based operational framework, a day-ahead optimal scheduling strategy and model for cluster smart buildings considering the overall power balance and consumer preferences and behaviors is proposed. The objective of the optimal scheduling strategy for cluster smart buildings is to minimize the total energy procurement cost.

The remainder of this study is organized as follows. An operational framework for a smart community with multiple buildings is described in Section 2. In Section 3, the water heater (WH) model, heating, ventilating and air conditioning (HVAC) model, EVs model and PVs model are established, respectively. On the basis, a day-ahead optimal scheduling strategy and model for cluster
smart buildings with the purpose of maximizing the economic interests as well as respecting DERs’ physical and comfort constraints is proposed. In Section 4, the simulation setup and parameters for this study is described and the numerical results obtained are discussed with the conclusion in Section 5.

2. System operational framework

Figure 1 presents a market-based operational framework for a smart community with multiple buildings, consisting of TCLs, EVs, fixed loads, and PV, as suggested in [6]. The smart community as a price-taker, participates in the wholesale electricity market. The operational procedure is as follows. Firstly, based on the ex-ante wholesale market prices audited by transmission system operator (TSO), predicted information of the DERs, and conventional demands, each building EMS operates the DERs with the purpose of maximizing the economic interests as well as respecting DERs’ physical and comfort constraints. Then, the building EMS submits its optimal schedule to the smart community. Finally, the smart community as an agent, participates in the wholesale market participates in the wholesale electricity market. It should be noted that the point where all the smart buildings and the transformer unit have a common connection in Figure 1.

3. Optimal scheduling strategy and model

3.1. TCLs model

3.1.1. Water heater model

The temperature dynamics of $k$-th hot water tank are described by resistance-capacitance circuit model [7].

$$C_{wh} \frac{d\theta_{k,i}^{wh}}{dt} = q_{k,i}^{wh} - q_{k,i}^{hwd} + \frac{\theta_{amb}^h - \theta_{k,i}^{wh}}{R_{wh}}$$

(1)

where, $C_{wh}$, $R_{wh}$ are the thermal capacitance and the thermal resistance of the hot tank; $\theta_{k,i}^{wh}$, $\theta_{amb}^h$ are the temperature of hot water and ambient temperature, respectively; $q_{k,i}^{wh}$ is the heat input from the water heater; $q_{k,i}^{hwd}$ represents the demand heat for hot water by the building, which can be represented by (2a).

$$q_{k,i}^{hwd} = C_p \rho V_i^{hwd} (\theta_{k,i}^{wh} - \theta_{amb}^h)$$

(2a)

where, $C_p$ is the specific heat capacity of water (4.2×10^3 J/(kg·℃)); $\rho$ is the density of water (1kg/L); $V_i^{hwd}$ represents the demand volume of $k$-th hot water. The relationship between $\theta_{k,i}^{wh}$, $q_{k,i}^{wh}$ and $\theta_{k,i}^{amb}$ can be expressed in the following discrete form.
\[ \theta_{x,j,i}^{wh} = a \theta_{x,j}^{wh} + b q_{k,j}^{wh} + c \theta_{l}^{amb} \]  

(2b)

where \( a, b \) and \( c \) are described in detail, as follows:

\[
\begin{align*}
 a &= 1 - \frac{\Delta t}{R_{wh} C_{wh}} - \frac{C_{p} \rho V_{wh}^{k,j}}{C_{wh}} \\
b &= \frac{\Delta t}{C_{wh}} \\
c &= \frac{\Delta t}{R_{wh} C_{wh}} + \frac{C_{p} \rho V_{wh}^{k,i}}{C_{wh}}
\end{align*}
\]

(2c)

Assume that the power of the water heater is completely converted into the demand heat for hot water \( p_{k,j}^{wh} = q_{k,j}^{wh} \). In addition, the hot water temperature must be kept within the acceptable range to meet the water temperature requirement of occupants.

\[
\theta_{min}^{wh,j} \leq \theta_{l,j}^{wh} \leq \theta_{max}^{wh,j} \\
0 \leq p_{k,j}^{wh} \leq p_{max,k}^{wh}
\]

(2d)

(2e)

where, \( \theta_{min}^{wh,j} \) and \( \theta_{max}^{wh,j} \) represent minimum and maximum hot water temperatures limits, respectively; \( p_{max,k}^{wh} \) is the accepted maximum power. In the \( h \)-th building, the total power consumption of \( N_{wh} \) water heaters is given by

\[ p_{h,j}^{wh} = \sum_{k=1}^{N_{wh}} p_{k,j}^{wh} \]  

(2f)

### 3.1.2. HVAC model

The thermal dynamics of \( m \)-th HVAC system are described as follows [7].

\[
\frac{d \theta_{m,j}^{e}}{dt} = \frac{1}{C_{a}} \left[ \xi W Q_{rad} + V_{aw} (\theta_{m,j}^{w} - \theta_{m,j}^{e}) S \right] - \text{COP} p_{hvac,j}^{m,t} 
\]

(3a)

\[
\frac{d \theta_{m,j}^{w}}{dt} = \frac{1}{C_{w}} \left[ \xi W Q_{rad} + V_{aw} (\theta_{m,j}^{w} - \theta_{m,j}^{w}) S \right] - V_{we} (\theta_{l,j}^{amb} - \theta_{m,j}^{w}) S 
\]

(3b)

where, \( \theta_{m,j}^{e} \) and \( \theta_{m,j}^{w} \) present the indoor temperature and the wall temperature, respectively; \( C_{a} \) and \( C_{w} \) the thermal capacitance of the indoor environment and the wall; \( Q_{rad}, \xi \) are the solar irradiation and the efficiency factor of the solar radiation, respectively; \( V_{we}, V_{aw} \) represent the heat transfer rate between the wall and the outside and between the indoor and the wall, respectively. \( W, S \) are the area of wall and window; COP is the coefficient of performance of the chiller; \( p_{hvac,j}^{m,t} \) is the HVAC load.

The second-order thermodynamic model of the HVAC systems can be written compactly in the following discrete form.

\[
\theta_{m,j+1}^{e} = f(\theta_{m,j}^{e}, \theta_{m,j}^{w}, p_{hvac,j}^{m,t} , d_{t}^{e}) 
\]

(4a)

\[
\theta_{m,j+1}^{w} = f(\theta_{m,j}^{w}, \theta_{m,j}^{e}, d_{t}^{w}) 
\]

(4b)

where, \( d_{t}^{e}, d_{t}^{w} \) is the disturbance vector, including some measurement errors from ambient temperature and solar irradiation. Note that building EMS has responsibility to keep a comfortable environment for the occupants. Furthermore, when the number of dispatching HVACs is large, it can be assumed that each HVAC has continuous power input instead of binary power input of \( \{0, p_{max,hvac}^{m,t}\} \), \( p_{max,hvac}^{m,t} \) is the accepted maximum power. The temperature limits and the HVAC power limits are enforced by
\[ \theta_t^\text{min} \leq \theta_t^a \leq \theta_t^\text{max} \quad t \in T_{m}^{\text{occ}} \]
\[ 0 \leq p_{h,t}^{\text{hvac}} \leq p_{h,\text{max}}^{\text{HVAC}} \]

where \( \theta_t^\text{min} \), \( \theta_t^\text{max} \) are the temperature boundaries specified by the occupants when occupants are present; \( T_{m}^{\text{occ}} \) is the accepted controlling periods. In the \( h \)-th building, the total power consumption of \( Nh \) HVACs is given by
\[ p_{h,t}^{\text{hvacs\sum}} = \sum_{m=1}^{M_{h}} p_{m,t}^{\text{hvac}} \]

3.2. EV model
The EV model is described by (5) for the \( i \)-th EV.
\[ p_{i,t}^{\text{evdis}} / \eta^\text{dis} = p_{i,t}^{\text{ev,used}} + p_{i,t}^{\text{ev,sell}} \]
\[ 0 \leq p_{i,t}^{\text{evch}} \leq p_{i,t}^{\text{max}} \mu_{i}^{\text{evch}} \]
\[ 0 \leq p_{i,t}^{\text{evdis}} \leq p_{i,t}^{\text{min}} (1 - \mu_{i}^{\text{evch}}) \]
\[ SOC_{0,i} + \sum_{t=1}^{T_{i}} \Delta \left( p_{i,t}^{\text{evch}} \eta^\text{ch} - p_{i,t}^{\text{evdis}} / \eta^\text{dis} \right) A_{i,t} / Q_{i} \geq SOC_{c,i} \]
\[ SOC_{i+1} = SOC_{i} + \sum_{t=1}^{T_{i}} \Delta \left( p_{i,t}^{\text{evch}} \eta^\text{ch} - p_{i,t}^{\text{evdis}} / \eta^\text{dis} \right) A_{i,t} / Q_{i} \]
\[ SOC_{i}^{\text{max}} \geq SOC_{i} \leq SOC_{i}^{\text{max}} \]

where \( p_{i,t}^{\text{evch}}, p_{i,t}^{\text{evdis}} \) are the charging and the discharging power of an individual \( i \)-th EV, respectively; \( p_{i,t}^{\text{ev,used}} \) satisfy the \( h \)-th building’s power demand; \( p_{i,t}^{\text{ev,sell}} \) is portion of the EV power of the \( h \)-th building injected to common connection in the smart community; \( A_{i,t} \) is grid-connected status of \( i \)-th EV in period \( t \), the value will be 0 or 1; \( \eta^\text{ch} \) and \( \eta^\text{dis} \) are charging and discharging efficiency of the \( i \)-th EV, respectively; \( p_{i,t}^{\text{max}}, p_{i,t}^{\text{min}} \) are the power limits, respectively; the binary variables \( \mu_{i}^{\text{evch}} \) are necessary in the mathematical model in order to enforce the fact that the EV may only charge or discharge at a given time interval; \( SOC_{i}, SOC_{c,i} \) is the state of the EV charge; \( SOC_{0,i}, SOC_{i}^{\text{max}}, SOC_{i}^{\text{min}} \) are the state limits; \( T_{i}, T_{eq,i} \), are on-grid time and off-grid time.

3.3. PV model
The \( h \)-th building’s PV output \( p_{h,t}^{\text{pv}} \) can be decomposed into two parts:
\[ p_{h,t}^{\text{pv}} = p_{h,t}^{\text{pv,used}} + p_{h,t}^{\text{pv,sell}} \]
where \( p_{h,t}^{\text{pv,used}} \) satisfy the \( h \)-th building’s power demand; \( p_{h,t}^{\text{pv,sell}} \) is portion of the PV power of the \( h \)-th building injected to common connection in the smart community.

3.4. Smart community optimal scheduling model
3.4.1. Objective function
The objective of the \( h \)-th smart building is to minimize the total energy procurement cost:
\[ \text{cost}_h = \min \sum_{i=1}^{T} \left( (p_{h,i}^{\text{buy}} C_i^{\text{buy}} - p_{h,i}^{\text{sell}} C_i^{\text{sell}}) \Delta t + (C_{i}^{\text{deg}} \sum_{i=1}^{T} \sum_{j=1}^{N_{\text{ev}}} p_{j,i}^{\text{evdis}}) \Delta t \right) \]  

(7)

where \( C_i^{\text{buy}} \) and \( C_i^{\text{sell}} \) are purchasing price and sale price from the wholesale electricity market, respectively; \( p_{h,i}^{\text{buy}} \) is the total power procured by \( h \)-th smart building; \( p_{h,i}^{\text{sell}} \) is the total power injected to the common connection point by \( h \)-th smart building; \( C_{i}^{\text{deg}} \sum_{i=1}^{T} \sum_{j=1}^{N_{\text{ev}}} p_{j,i}^{\text{evdis}} \) represents the costs from EVs’ battery degradation when discharging energy from the EVs to the grid; \( C_{i}^{\text{deg}} \) is degradation costs per unit of processed energy; \( N_{\text{ev}} \) represents the number of the \( h \)-th smart building. The objective of the smart community consisting of \( N_h \) buildings is as follows:

\[ \min \sum_{h=1}^{N_h} \text{cost}_h \]  

(8)

3.4.2. Neighborhood power exchange

\( p_{h,j}^{\text{buy}} \) and \( p_{h,j}^{\text{sell}} \) can be decomposed into equation (9), (10).

\[ p_{h,j}^{\text{buy}} = p_{h,j}^{\text{buy,g}} + p_{h,j}^{\text{buy,h}} \]  

(9)

\[ p_{h,j}^{\text{sell}} = p_{h,j}^{\text{sell,g}} + p_{h,j}^{\text{sell,h}} \]  

(10)

where \( p_{h,j}^{\text{buy,g}} \) is the power from grid; \( p_{h,j}^{\text{buy,h}} \) is the power from the other buildings; \( p_{h,j}^{\text{sell,g}} \) is the portion of the power injected to point of common connection by building that flows back to grid; \( p_{h,j}^{\text{sell,h}} \) is the power to the other buildings. Furthermore, the injected power to be used in the \( N_h \) buildings should be equal to the power that is being gathered from local sources at every given period as enforced by equation (11).

\[ \sum_{h=1}^{N_h} p_{h,j}^{\text{buy}} = \sum_{h=1}^{N_h} p_{h,j}^{\text{sell}} \]  

(11)

Constraints (12) limit the total energy that the neighborhood may procure by the transformer and vice versa, respectively. \( P_i^{\text{ran}} \) is power limit of the transformer; \( \mu_i^{\text{ran}} \) is the binary variables.

\[ 0 \leq \sum_{h=1}^{N_h} p_{h,j}^{\text{buy,g}} \leq P_i^{\text{ran}} \mu_i^{\text{ran}} \]  

(12a)

\[ 0 \leq \sum_{h=1}^{N_h} p_{h,j}^{\text{sell,g}} \leq P_i^{\text{ran}} (1 - \mu_i^{\text{ran}}) \]  

(12b)

3.4.3. Power balance

The power balance of the \( h \)-th building is described by equation (13).

\[ p_{h,j}^{\text{load}} + p_{h,j}^{\text{pv,used}} + \sum_{i=1}^{N_{\text{ev}}} (p_{i,j}^{\text{ev,used}}) = p_{h,j}^{\text{load}} + \sum_{i=1}^{N_{\text{ev}}} (p_{i,j}^{\text{ev,exch}}) + p_{h,j}^{\text{hvacsum}} + p_{h,j}^{\text{whsum}} \]  

(13)

where \( p_{h,j}^{\text{load}} \) represents fixed load of the \( h \)-th building. Constraints (14) (15) define the energy transactions between the buildings and the grid.

\[ p_{h,j}^{\text{sell}} = p_{h,j}^{\text{pv,sell}} + \sum_{i=1}^{N_{\text{ev}}} (p_{i,j}^{\text{ev,sell}}) \]  

(14)

\[ 0 \leq \sum_{h=1}^{N_h} p_{h,j}^{\text{buy}} \leq N \mu_h^b \]  

(15a)

\[ 0 \leq p_{h,j}^{\text{sell}} \leq N(1 - \mu_h^b) \]  

(15b)
where the parameter $N$ is set to sufficiently high positive value; the binary variables $\mu_{h,t}$ are necessary in the mathematical model in order to enforce the fact that the $h$-th building may only draw or inject at a given time interval.

### 4. Simulation setup and results

#### 4.1. Case parameters

In this study, the optimization is addressed through the YALMIP toolbox together with CPLEX12.6 solver in the MATLAB2015a platform. The scheduling period is from 12:00 to 12:00 of the next day with a 15-min interval.

| Parameter | Value | Parameter | Value |
|-----------|-------|-----------|-------|
| $C_{wh}$ (J/°C) | $2.1 \times 10^5$ | $R_{wh}$ (°C/kW) | 3170 |
| $C_a$ (J/°C) | $9.2 \times 10^6$ | $V_{av}$ (kW/m².°C) | 0.01 |
| $C_w$ (J/°C) | $2.6 \times 10^7$ | $V_{we}$ (kW/m².°C) | 0.04 |
| $\theta^m$ (°C) | [45, 50] | $P_{wh}^{max}$ (kW) | 2 |
| $\theta^e$ (°C) | [24, 28] | $P_{hvac}^{max}$ (kW) | 2.5 |

The ex-ante wholesale market prices used for scheduling the smart buildings are referred to [6]. It is assumed that there are 3 buildings in the smart community. Building 1 has 50 HVACs, 50 WHs, 80 EVs, PV and conventional loads; Building 2 has 50 HVACs, 50 WHs and conventional loads without power generation set; Building 3 has 80 EVs, PV and conventional loads. EV has a capacity of 64 kWh, operated between 10 and 95% state of charge. The limited charging and discharging power for EV is ±7 kW and its efficiency is 0.95. The trip consumption is also assumed to be uniformly distributed at 1.5 kWh around the reference value, referred to in [8]. Assume that a WH with a capacity of 25 L is always full. The solar irradiation data is from [9] and the solar radiation efficiency $\xi$ is set as 2/3. $S$ and $W$ are set as 30 and 8 $m^2$, respectively. The COP of the chiller is 3. The profiles of building and other related parameters of TCLs are listed in Table 1 [7]. The total capacity of transformer is 3200 KVA, and its maximum load rate is 0.65 [10]. The PV productions and the fixed loads data can be seen in 4.2.

#### 4.2. Results and discussion

The smart building EMS responds to the guidance of the incentive signals from wholesale market while respecting the physical and environmental impacts of the TCLs. In Figure 2, it is observed that the impact of different factors of HVAC on power consumption is related to the ambient temperature, the wall materials, and the occupants’ comfort zone. Note that although the outdoor temperature drops...
around 13:00-16:00, the wall temperature still rises because the model considers the interference of solar radiation on the wall. Meanwhile, owing to the building thermal inertia, HVAC keeps the indoor temperature as low as possible in the economical period and to reduce the power consumption in the peak periods.

Figure 3 illustrates that the power distribution of WH is mainly affected by the demand for hot water besides electricity price. Similar to HVAC, WH increases the power consumption as much as possible in the cheaper price and thus reduces the power consumption at peak price.

Figure 4 - 6 show that the power balance situation of each smart building. We can see these are periods of relatively high prices and as a result the smart building EMS attempts to avoid buying power from the grid. In Figure 4, we can see the EVs connected to grid from the building 1 all choose to charge at the time when the purchasing electricity price is low. During 6:00 - 17:30, the PV of building 1 is used to meet its own power demand. Moreover, V2B (vehicle-to-building) is also carried out from 6:00 to 11:00. In Figure 5, because building 2 do not have PV and EV, the power demand are from other buildings and grid.

The portion of the power purchased by building 1 and building 2 are from the building 3 during the period 8:00 - 16:00. This is mainly because there is an amount of surplus PV output in the building 3. In addition, compared with building 1 and building 2 from Figure 4 - 5, building 3 purchases less power from the grid. In Figure 7, the smart building 3’s PV output can be decomposed into two parts:
one part satisfies its power demand and another part is injected to common connection in the smart community.

Figure 6. Power distribution of smart building 3

Figure 7. Power distribution of PV from smart building 3

Figure 8. Power distribution of smart community

Figure 9. Power curve under consideration or no consideration of transformer power limit
Figure 8 shows the power distribution of the smart community. The decomposition of the total power that is procured by the smart buildings into the power from grid; and the power from the other buildings. The reverse power injected to the grid is mainly from the PV productions of the smart buildings. In addition, the power sharing was carried out between 6:00 and 17:30. As a further study, the impact of the distribution transformer load on the results of day-ahead optimal schedule is presented in Figure 9. It can be seen that fully leveraging the flexibilities available from smart buildings with high proportion of DERs can contribute to improving the operational life of transformers.

5. Conclusion
In this study, a market-based operational framework for cluster smart buildings is proposed. Each smart building EMS operates various DERs to minimize the total energy procurement cost as well as observe physical and comfort constraints. On this basis, a day-ahead optimal scheduling strategy and model for cluster smart buildings considering the overall power balance and consumer preferences and behaviors is proposed. Finally, the numerical results indicate that the proposed model can achieve local power sharing in the smart community, and show that fully leveraging the flexibilities available from smart buildings with high penetration of DERs can bring economic benefits to the end-users and the grid.

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References
[1] Ozan Erdinc, Nikolaos G. Paterakis, Tiago D. P. Mendes, et al. Smart Household Operation Considering Bi-Directional EV and ESS Utilization by Real-Time Pricing-Based DR[J]. IEEE Transactions on Smart Grid, 2015, 6(3): 1281-1291.
[2] D S Callaway, I A Hiskens. Achieving Controllability of Electric Loads[J]. Proceedings of the IEEE, 2011, 99(1): 184-199.
[3] X. Zhang, J. Yang, Y. Huang. A two-stage dispatch optimization for electric vehicles and controllable load in PV intelligent community[J]. Power System Technology, 2016, 40(9): 2630-2637.
[4] G. Liu, Y. Xu, K. Tomsovic. Bidding Strategy for Microgrid in Day-ahead Market Based on Hybrid Stochastic/robust Optimization[J]. IEEE Transactions on Smart Grid, 2016, 7(1): 227-237.
[5] Y. Liu, C. Yuen N U Hassan, et al. Electricity cost minimization for a microgrid with distributed energy resource under different information availability[J]. IEEE Transactions on Industrial Electronics, 2015, 62(4): 2571-2583.
[6] J. Wu, X. Ai, Y. Zhang, et al. Day-Ahead Optimal Dispatching for High Penetration of Distributed Energy Resources in Community under Separated Distribution and Retail Operational Environment[J]. Power System Technology, 2018:42(6): 1709-1717.
[7] X. Ai, J. Wu, J. Hu, et al. Distributed Congestion Management of Distribution Networks to Integrate Prosumers Energy Operation[J]. IET Generation, Transmission & Distribution, 2020: 14(15): 2988-2996.
[8] Z. Luo, Z. Hu, Y. Song, et al. Study on Plug in Electric Vehicles Charging Load Calculating[J]. Automation of Electric Power Systems, 2011, 35(14): 36-42.
[9] N. Lu. An Evaluation of the HVAC Load Potential for Providing Load Balancing Service[J]. IEEE Transactions on Smart Grid, 2012, 3 (3): 1263-1270.
[10] Y. Guo, Z. Hu, H. Zhang, et al. A Statistical Method to Evaluate the Capability of Residential Distribution Network for Accommodating Electric Vehicle Charging Load[J]. Power System Technology, 2015, 39(9): 2458-2464.