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Coordinated optimization of multiple buildings with a fair price mechanism for energy exchange☆

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ABSTRACT

This paper focuses on the jointly operational optimization of a network of buildings while considering energy exchange among them. Based on the operation model of each individual building, coordinated information and strategies of the energy exchange among all buildings are used to maximally reduce the energy cost of all the buildings while reducing the complexity of the network operation. The optimization problem of a network of multiple buildings is formulated as a stochastic mixed integer programming problem, and a Lagrangian relaxation-based decentralized algorithm is developed to solve this problem. Based on this method, a price mechanism for the energy exchange among buildings which can guarantee the fairness of all the buildings is developed by introducing Lagrangian multipliers as the coordinated signals for the decentralized optimization. The performance of the proposed method is discussed based on case studies of a network of four buildings in Singapore. Numerical results show that the method can not only achieve significant energy cost savings for all the buildings, but also provide huge ability to accommodate the uncertainties in the network. It is also found that the proposed price mechanism for the energy exchange provides incentives for the buildings to participate in the joint optimization.

1. Introduction

Building sector accounts for 40% of total energy consumption according to the statistical results [1], the amount of which is still increasing acutely. In terms of alleviating the energy crisis and environmental pollution, improving building energy efficiency has become more important and necessary in recent years. There are two ways to improve the building energy efficiency. One is to integrate the renewable energy resources (such as solar PV panels and wind power) and storage devices (such as battery and water tank) into the building energy systems. Another one is to optimize the building operation, in order to minimize the energy cost and peak demand while providing the desirable indoor environment for occupants.

Recently, operational optimization of an individual building has been studied extensively. The results showed that the energy efficiency of individual building energy systems can be significantly improved by the existing methods, such as mixed integer programming [2], model predictive control [3], simulation-based optimization [4], etc. However, there are limits on the operational optimization of the individual building. On the one hand, occupants' behaviors and requirements, outdoor environment, and operational efficiency of energy devices may limit the building energy efficiency. On the other hand, uncertainties in the supply (such as renewable energy resources) and demand (such as electrical and thermal demand profiles) have huge impact on the energy efficiency.

Alternatively, joint optimization of a network of buildings that are interconnected to the same distribution line is an effective way to relax the above-mentioned limits and further improve the energy efficiency of all the buildings, due to the following two reasons: 1) The joint optimization can utilize the complement of the demand profiles of different buildings to effectively improve the energy efficiency of each building; and 2) The joint optimization may provide more flexibility for all the buildings to accommodate the uncertainties in the supply and demand. Many studies have been made to jointly optimize the operation of multiple buildings, which can be classified into two groups. The first group considers

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Nomenclature

Index

i, j	Index of building in the network, with $i = 1,2,\ldots,M$, $j = 1,2,\ldots,M$
k	Stage index, with $k = 1,2,\ldots,K$
so	Scenario index of the occupancy factor, with $so = 1,2,\ldots,S_o$
ss	Scenario index of the solar radiation, with $ss = 1,2,\ldots,S_s$

Parameters

$b_{c,i}$	The investment cost of the battery in building i (S$)
$b_{l,i}$	The cycle lifetime of the battery in building i
c_d^k	The price of electricity bought from the power grid at k (S$/kWh)
c_u^k	The price of electricity fed into the power grid at k (S$/kWh)
$\bar{e}_{b,i}$	The capacity of the battery in building i (kWh)
K	The total number of the stages over the scheduling horizon
K_i^{on}	The required working time of the washer in building i (h)
M	The total number of the buildings in the network
MSD_i	The set of stages at which the washer in building i is forbidden to work
$N_{pp,i}$	The number of parallel PV cells in the PV panel of building i
$N_{ss,i}$	The number of series PV cells in the PV panel of building i
$\overline{p}_{d,i}$	The capacity limit of the power supplied from the power grid to building i (kW)
$\underline{p}_i^{bc}$	The lower bound of the charging power of the battery in building i (kW)
$\overline{p}_i^{bc}$	The upper bound of the charging power of the battery in building i (kW)
$\underline{p}_i^{bd}$	The lower bound of the discharging power of the battery in building i (kW)
$\overline{p}_i^{bd}$	The upper bound of the discharging power of the battery in building i (kW)
$\overline{p}_{u,i}$	The capacity limit of the power fed into the power grid from building i (kW)
$\overline{p}_{\langle i,j \rangle}$	The capacity limit of the transmission line between buildings i and j (kW)
$p_{w,i}$	The mean power of the washer in building i (kW)
R_i	The total number of the rooms in building i
S_o	The total number of the scenarios of the occupancy factor
S_s	The total number of the scenarios of the solar radiation
$\underline{V}_i^b$	The lower bound of the state of charge (SOC) of the battery in building i
$\overline{V}_i^b$	The upper bound of SOC of the battery in building i
$\gamma_{\langle i,j \rangle}$	The coefficient for the energy loss of the transmission line between buildings i and j
$\mu_{b,i}$	The coefficient for the energy degradation of the battery in building i
π_{so}	The probability of the so-th scenario of the occupancy factor
π_{ss}	The probability of the ss-th scenario of the solar radiation
τ	The length of time in each stage (h)

Continuous variables

$C_{b,i}^k$	The penalty of the cycle lifetime for the battery in building i at k (S$)
$e_{d,i}^k$	The energy supplied from the power grid to building i at k (kWh)
$e_{hv,i}^k$	The energy consumption of the chiller of HVAC in building i at k (kWh)
$e_{u,i}^k$	The energy sold to the power grid from building i at k (kWh)
$e_{\leftarrow j}^{i,k}$	The energy supplied from building j to building i at k (kWh)
$e_{\rightarrow j}^{i,k}$	The energy sold to building j from building i at k (kWh)
$I_{cell,i}^k$	The output current of the PV cell in the PV panel of building i at k (A)
$l_{w,i}^k$	The energy consumption of the washer in building i at k (kWh)
$p_{bc,i}^k$	The charging power of the battery in building i at k (kW)
$p_{bd,i}^k$	The discharging power of the battery in building i at k (kW)
$p_{s,i}^k$	The output power of the solar PV panels in building i at k (kW)
$q_{fcu,i}^k$	The thermal energy supplied by the FCU in all the rooms of building i at k (kWh)
s_i^k	SOC of the battery in building i at k
$V_{cell,i}^k$	The output voltage of the PV cell in the PV panel of building i at k (V)

Discrete variables

w_i^k	"1" if the washer in building i works at k; "0" otherwise
$y_{w,i}^k$	"1" if the washer in building i shuts down at k; "0"otherwise
$z_{bc,i}^k$	"1" if the battery in building i is charged at k; "0" otherwise
$z_{bc,c,i}^k$	"1" if the battery in building i starts charging at k; "0" otherwise
$z_{bd,i}^k$	"1" if the battery in building i is discharged at k; "0" otherwise
$z_{bd,d,i}^k$	"1" if the battery in building i starts discharging at k; "0" otherwise
$z_{d,i}^k$	"1" if building i buys the energy from the power grid at k; "0" otherwise
$z_{u,i}^k$	"1" if building i sells the energy to the power grid at k; "0" otherwise
$z_{w,i}^k$	"1" if the washer in building i starts up at k; "0"otherwise
$z_{\leftarrow j}^{i,k}$	"1" if building i buys the energy from building j at k; "0" otherwise
$z_{\rightarrow j}^{i,k}$	"1" if building i sells the energy to building j at k; "0" otherwise

the joint optimization through the centralized methods. For example, Minciardi and Sacile [5] formulated the optimization problem of a cooperative network of smart power grids as a linear quadratic Gaussian problem and developed a centralized algorithm to obtain the solution. Ouammi et al. [6] developed a centralized control method for optimal management of a network of microgrids to obtain the optimal strategy of power flows in