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A distributed decision framework for building clusters with different heterogeneity settings

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HIGHLIGHTS

- A self-organizing map based clustering algorithm is developed.
- A homogeneity index is proposed to quantitatively evaluate building clusters.
- A genetic algorithm based bi-level distributed decision framework is proposed.
- Shared renewable energy and battery are preferred for heterogeneous building clusters.

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ABSTRACT

In the past few decades, extensive research has been conducted to develop operation and control strategy for smart buildings with the purpose of reducing energy consumption. Besides studying on single building, it is envisioned that the next generation buildings can freely connect with one another to share energy and exchange information in the context of smart grid. It was demonstrated that a network of connected buildings (aka building clusters) can significantly reduce primary energy consumption, improve environmental sustainability and building's resilience capability. However, an analytic tool to determine which type of buildings should form a cluster and what is the impact of building clusters' heterogeneity based on energy profile to the energy performance of building clusters is missing. To bridge these research gaps, we propose a self-organizing map clustering algorithm to divide multiple buildings to different clusters based on their energy profiles, and a homogeneity index to evaluate the heterogeneity of different building clusters configurations. In addition, a bi-level distributed decision model is developed to study the energy sharing in the building clusters. To demonstrate the effectiveness of the proposed clustering algorithm and decision model, we employ a dataset including monthly energy consumption data for 30 buildings where the data is collected every 15 min. It is demonstrated that the proposed decision model can achieve at least 13% cost savings for building clusters. The results show that the heterogeneity of energy profile is an important factor to select battery and renewable energy source for building clusters, and the shared battery and renewable energy are preferred for more heterogeneous building clusters.

1. Introduction

In the United States, buildings are responsible for over 70% of electricity consumption with approximately half from commercial sources and the remainder from residential [1]. Buildings are also responsible for approximately 40% of CO_2 emissions, which is more than any other sector [2]. However, 4–20% of energy used for heating, ventilating and air conditioning (HVAC), lighting and refrigeration in a building is wasted due to the problems with system operation [3]. Therefore a new concept, *smart building,* that aims to reduce a building's primary energy consumption is being promoted by the United States Department of Energy [4]. In the past decades, extensive research has been conducted to develop operation/control strategies to improve building energy performance which can be classified into two categories: (1) single building

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Nomenclature

Indices

j	index of houses
t	index of time interval

Subscriptions

bat	battery
act	active
dis	dispatch
cha	charging
disch	discharging
pow	powering
sel	selling
con	conversion
hou	house
gri	grid
pur	purchase
loa	load
sp	solar power

Variables

Household variable

Sb_act_{jt}	state of battery being active for house j at time t (0: dormant; 1: active)
Sb_cha_{jt}	state of battery being charging for house j at time t (0: not charging; 1: charging)
Sb_disch_{jt}	state of battery being discharging for house j at time t (0: not discharging; 1: discharging)
Sb_sel_{jt}	state of battery selling energy for house j at time t (0: not selling; 1: selling)
Sb_pow_{jt}	state of battery powering house j at time t (0: not powering; 1: powering)
C_j	the cost for house j
CRS_{jt}	the state of charge of battery for house j at time t
$Ppur_{jt}$	the amount of purchased energy for house j at time t
$Pdis_{jt}$	the amount of energy dispatched from external sources to house j at time t
$Psel_{jt}$	the amount of energy sold by house j at time t
$Ploa_{jt}$	the amount of energy load for house j at time t
Pb_cha_{jt}	the amount of charging power of battery for house j at time t
Pb_disch_{jt}	the amount of discharging power of battery for house j at time t

Complex variable

Sb_act_t	state of battery being active at time t (0: dormant; 1: active)
Sb_cha_t	state of battery being charging at time t (0: not charging; 1: charging)
Sb_disch_t	state of battery being discharging at time t (0: not discharging; 1: discharging)
Sb_sel_t	state of battery selling energy at time t (0: not selling; 1: selling)
Sb_pow_t	state of battery powering the complex at time t (0: not powering; 1: powering)
Ssp_act_t	the state of the solar power at time t (0: not active; 1: active)
Ssp_sel_t	the state of the solar power selling at time t (0: not selling; 1: selling)
Ssp_pow_t	the state of the solar power powering at time t (0: not powering; 1: powering)
Pb_dis_{jt}	the amount of electricity dispatched from battery complex to house j at time t
$Phou\_dis_{jt}$	the amount of electricity dispatched from other houses extra energy to house j at time t
Psp_dis_{jt}	the amount of electricity dispatched from solar power to house j at time t
C	The cost of complex
CRS_t	The state of charge of battery at time t
$Ppur\_gri_t$	the amount of purchased energy at time t from grid
$Psel_t$	the amount of sold energy at time t
$Ploa_t$	the amount of electricity load at time t
Pb_cha_t	The amount of charging power of the battery at time t
Pb_disch_t	the amount of discharging power of the battery at time t
Psp_t	the amount of solar power at time t

Parameters

T	decision time horizon (e.g., 24 h)
n	number of houses
η_{con}	the battery AC/DC convertor efficiency
TID	decision time interval duration (e.g., 15 min)
$Rgri_t$	the price of energy in grid at time t
$Rbat_t$	the price of energy provided by battery at time t
$Rhou_t$	the price of energy provided by other houses at time t

Household parameters

$Cbat_j$	the full capacity of battery in house j
Λ_j	charging rate of battery at house j
Π_j	discharging rate of battery at house j

Complex parameters

Λ	charging rate of battery
Π	discharging rate of battery

operation, and (2) multiple buildings (aka building clusters) operation.

It was demonstrated that pre-cooling can efficiently utilize building thermal mass to reduce energy consumption and achieve cost savings [5]. This motivates researchers to develop efficient operation strategy for building energy system, such as optimal operation using dynamic programming [6], real-time predictive supervisory operation [7], fuzzy rule based operation [8], just to name a few. The concept of demand-side management (DSM) [9] in building operation deals with different optimization methods such as mathematical modeling and game theory to decrease energy cost while maintaining an acceptable comfort level. Controlling building thermal mass, thermal storage system [10], electric storage devices and on-site electricity generator [11] are the subjects of this line.

Other than operation/control of single building, the benefits of connected multiple buildings (aka building clusters) to share energy are also explored. The study focused on building clusters where there are at least two buildings has received unprecedented attention. Due to the transparency that smart grid has given to energy management, energy users and researchers have come up with strategies for shifting peak load and saving energy cost by physically or virtually connecting multiple buildings. In addition, recent studies have explored other benefits including reduction in peak load, load energy shifting from higher-load hours to lower-load hours, and reduction of load variability [12,13].

The initial study of building clusters demonstrated that building clusters are able to significantly reduce energy consumption and improve environmental sustainability [3]. However, the existing research only answered the question that why multiple buildings