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Occupancy-based buildings-to-grid integration framework for smart and connected communities

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HIGHLIGHTS

- Development of a centralized occupancy-based Buildings-to-grid Model Predictive Control (MPC) framework.
- Simulation on building clusters and standard IEEE grid systems.
- Findings show 50–61% cost reduction for BtG integration.

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ABSTRACT

Buildings-to-grid (BtG) integration simulations are becoming prevalent due to the development of smart buildings and smart grid. Buildings are the major energy consumers of the total electricity production worldwide. There is an urgent need to integrate buildings with smart grid operation to accommodate the needs of flexible load controls due to the increasing of renewable energy resources. In the imminent future, smart buildings can contribute to grid stability by changing their overall demand patterns in response to grid operations. Meanwhile, building thermal energy consumption is also maintained by building operators to satisfy occupants' thermal comforts. However, explicit large-scale demonstrations based on a simulation platform that integrates building occupancy, building physics, and grid physics at community level have not been explored. This study develops an occupancy behavior driven BtG optimization platform that can simulate, predict and optimize indoor temperature and energy consumption of buildings, generator setpoint and deviation while maintaining acceptable grid frequency. Authors have tested the framework on two standard power networks. The results show that the integrated framework can provide potential cost savings up to 60% comparing with the decoupled operation.

1. Introduction

In response to dramatic growth of power demand, use of renewable energy, and critical risk of building power blackouts, smart buildings and smart grid that can communicate with each other have more benefits for building management and power operation. Recent reports from the U.S. Department of Energy show that (1) buildings consume 74% of electricity produced by the grid in the U.S.; (2) buildings are able to reduce their consumption by 20–38% using advanced sensors and controls; and (3) 90% of the commercial buildings can be aggregated to connect to the grid [1–3]. Hence, it is necessary to investigate and understand the coupling between buildings and grids for optimizing the energy consumptions and the operation costs.

1.1. Building MPCs and research gaps

Model predictive control (MPC) is one real-time control algorithm that connects buildings to grids, thereby establishing a computational framework to co-optimize the decisions of building and grid operators. Studies interoperating buildings and grids using MPC for demand response are presented in recent literature overviews [4,5]. For commercial buildings, a bi-level MPC optimization is designed to control the voltage and current in a distribution grid while building zonal models are integrated [6]. The study provides a framework comprising mathematical models of commercial buildings and the distribution grid. Commercial building MPC or model-based supervisory control can also regulate the building power frequency by controlling the fan power consumption, the chiller operation sequence, and the air-side

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Nomenclature

Occupancy predictor

p	transition probability
α	distribution weight factor
β	smooth factor
s	occupancy state

Building system physics

C	thermal capacity
R	thermal resistance
T_{wall}	wall temperature
T_{zone}	zone temperature
Q	heat gain
Q_{sol}	solar heat
Q_{int}	internal heat
Q_{hvac}	HVAC cooling
η	HVAC coefficient of performance
$\mathbf{x_b}$	building temperature states
$\mathbf{u_b}$	building control inputs
$\mathbf{w_b}$	building disturbances

Grid system physics

θ	bus voltage angle
D	damping coefficient
M	inertia coefficient
P	power
P_m	mechanical power input
P_e	electricity demand load
P_{misc}	miscellaneous building load
P_{hvac}	building HVAC load
ω	bus frequency
$\mathbf{x_g}$	grid states
$\mathbf{u_g}$	building load to grid
$\mathbf{u_m}$	controllable mechanical powers to grid
$\mathbf{w_g}$	grid disturbances

BtG MPC

C	building cost as the grid price
ϵ	slack relaxation based on occupancy prediction
a	quadratic generator cost
b	linear generator cost
f	quadratic frequency cost

ventilation system [7,8]. Those studies treat buildings as fast demand side resources to reduce frequency deviations in grid operations. Customized designs of the model-based controllers can further provide ancillary services to the grid [9,10]. One study optimizes the chiller to respond fast to the demand response signal [9]. Another study investigates the ancillary service capacity under optimal HVAC usages [10]. For residential buildings, grid-aware MPCs are carried out to reduce the costs of smart homes by using energy storage, appliance scheduling, electric vehicles, and distributed generation units [11–15]. These studies usually focus microgrid or small-scale interactions between buildings and grids. The majority of the aforementioned research shows significant energy savings given different building systems with no account for larger scale simulations of building clusters.

One recent study [16] expands the current research scope by using a detailed physics model of a building cluster for a smart grid optimization. Although large-scale building aggregation is performed, the models of electricity generation and renewable energy source are oversimplified with no gird physics. Hence, the grid frequency and power flow transmission cannot be regulated. Furthermore, how to achieve the optimal control for hundreds of grid-aware commercial buildings is not demonstrated, especially considering the significant time-scale discrepancy between building demand change (minutes to hours) and grid power supply (milliseconds to seconds). Therefore, an explicit simulation of the building dynamics, grid dynamics, generator capacity, and BtG operation cost from a large-scale control strategy is a critical research question not fully addressed yet [17].

1.2. Missing of the occupant behavior

Another key component missing in the large scale BtG integration is the building occupancy. Humans spend more than 90% of their time in buildings, and the buildings themselves are designed to provide a comfortable indoor environment for occupants [18]. The human-building interactions, such as usage of lighting and air conditioning, consume around one quarter to half of the total amount of commercial building energy [19]. On the other hand, office workers arrive and leave the workspaces regularly according to schedules. The stochastic occupancy pattern can be detected easily by occupancy sensors, which are commonly installed in today's smart buildings [20]. Therefore, it is a natural idea to utilize the occupancy information to reduce the energy consumption caused by human-building interaction while maintaining occupants' comfort [21]. Typical occupancy schedules used to optimize building operations are conservative on energy savings [22]. Larger savings with stable comfort satisfactions can be further achieved through learning and prediction of the office occupancy [20].

Current research has found a range of strategies to predict and utilize the occupancy in single building control [23–25]. The optimization of air conditioning systems is demonstrated through building MPCs using the hidden Markov chain to predict the occupant numbers [26]. First order Markov chain (MC) is another popular method that can provide online occupancy predictions. One study trains a MC in a moving window for an occupancy driven MPC of commercial buildings [27]. The occupied periods are found by aggregated predictions of the occupancy models. The occupied periods' setpoint temperature of the air conditioning is reset from the high temperatures of unoccupied periods. A similar example is shown by penalizing the discomfort index during occupancy. Occupied periods are estimated using a MC that is trained through Bayesian inference [28]. Savings are shown by preheating, no conditioning at vacancies, and suppressing the peak demands. A more detailed description of the Markov model will be introduced in the following section of methodology. Other occupancy models have also been extensively explored for building simulations, such as random sampling [29], machine learning [30], data mining [31] and agent-based models [32]. However, most studies focus on the occupancy-buildings coupling are still ignoring the complete picture to associate occupancy, buildings, and grids together [33–35]. How those occupancy-based MPCs effect the aggregation of building demand and influence the optimization of grid operation remains largely unknown.

1.3. Innovations of the study

Based on the aforementioned review, the study addresses the following research gaps for a large scale BtG integration: (1) lack of investigation of advanced control strategies for the integration of occupancy, buildings and grid, and (2) lack of evaluation of the occupancy impact on the individual thermal comfort and energy savings. Three integration approaches are proposed and studied as: (1) a decoupled buildings and grid optimization (**DB&G**), (2) a centralized Buildings-to-Grid integration (**BtG**), and (3) a centralized occupancy-based BtG integration (**OBtG**). **DB&G** introduces on/off controls for buildings and