Computers, Environment and Urban Systems 62 (2017) 168–181

Contents lists available at ScienceDirect

Computers, Environment and Urban Systems

journal homepage: www.elsevier.com/locate/ceus

# Net-zero energy building clusters emulator for energy planning and operation evaluation

Xiwang Li [a,b,*], Jin Wen [b]

[a] Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, CA 94720, USA
[b] Department of Civil, Architectural and Environmental Engineering, Drexel University, Philadelphia, PA 19104, USA

ARTICLE INFO

*Article history:*
Received 19 April 2016
Received in revised form 27 September 2016
Accepted 28 September 2016
Available online xxxx

*Keywords:*
Net-zero building cluster
Net-zero buildings
Smart grids
Distributed energy systems
Co-simulation

ABSTRACT

The emergence of smart grids, Net-zero energy buildings, and advanced building energy demand response technologies continuously drives the needs for better design and operation strategies for buildings and distributed energy systems. It is envisioned that similar to micro-communities in a human society, neighboring buildings will have the tendency to form a building cluster, an open cyber-physical system to exploit the economic opportunities provided by smart grids and distributed energy systems. To realize this building cluster envision, it requires better urban energy planning and operation control strategies to determine which type of buildings should be clustered and what operation strategies should be implemented to fully utilize the potential in load aggregation, load shifting, and resource allocation. However, most of the current tools are focusing on single buildings or devices, which are not suitable for building cluster studies. To this end, this study proposes to develop a Net-zero building cluster emulator that can simulate realistic energy behaviors of a cluster of buildings and their distributed energy devices as well as exchange operation data and control schemes with real-world building control systems. The developed emulator has the flexibility to integrate with different buildings and distributed energy systems to study the performance of this building cluster to propose suggestions in urban energy planning and operation. To show the application of this emulator, a proof-of-concept demonstration is also presented in this paper.



## 1. Introduction

Buildings are responsible for more than 40% of primary energy and 70% of the electricity consumption in the United States (US DOE, 2013a), of which approximately 15–20% is wasted by nonoptimal control schemes and malfunction of equipment or performance degradation (Katipamula & Brambley, 2005). Moreover, the National Energy Technology Laboratory estimated that more than one-fourth of the 713 GW of US electricity demand in 2010 could be dispatchable if only buildings could respond to that dispatch through advanced building energy control and operation strategies and smart grid infrastructure (National Energy Technology Laboratory (NETL), 2011). Load dispatching is to determine the operation of generation facilities to produce energy at minimum cost to serve consumers reliably, which can assist the balance between power supply and demand in the power grids. Several distributed energy systems are developed and connected to the power grids, which brings in challenges to fully utilize the energy saving and reliability maintaining potentials. To this end, there is an urgent requirement to develop better control and operation strategies for buildings and distributed energy systems. Currently, with the spreading of smart grids, the power infrastructure in the United States is experiencing a revolutionary transformation, from a centralized one-way communication of power information to a decentralized network with two-way communication (Friedman, 2009). With the trend of moving from centralized building operation decision to decentralized operation control, it is envisioned that neighboring buildings will have the tendency to form a building cluster, within which smart grids, distributed power generation, and storage devices can freely share energy resource locally and globally and the entire cluster will achieve maximum energy efficiency (Hu, Weir, & Wu, 2012).

In this direction, this study proposes a Net-zero building cluster concept (Fig. 1). Different from the existing load aggregation concept, this building cluster concept may transform the energy industry by shifting expensive on-site energy generation aimed at creating single Net-zero building one-at-a-time to an autonomous and adaptive system of buildings aimed at Net-zero clusters. Through optimized demand management, these building clusters will likely reduce overall primary energy consumption and peak time electricity demand to be more resilient to power disruptions. Before this Net-zero building cluster concept, extensive studies have focused on Net-zero building development from the perspective of early design (Attia et al., 2012), renewable energy system integration (Dexter & Pakanen, 2001), and performance evaluation (Li, Wen, & Wu, 2014). Together with the Net-zero building studies,

* Corresponding author.
*E-mail addresses:* xiwangli@lbl.gov, xiwangli2010@gmail.com (X. Li).

http://dx.doi.org/10.1016/j.compenvurbsys.2016.09.007
0198-9715/

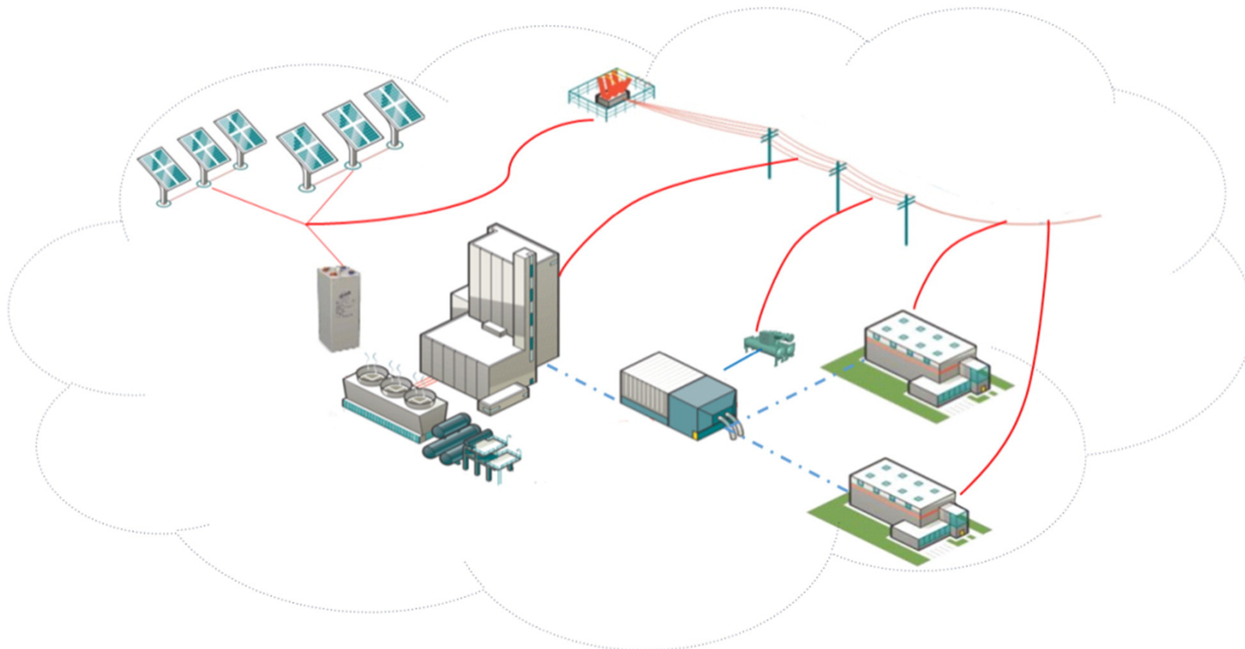

**Fig. 1.** Building cluster connection and operation.

research has also focused on developing operation strategies to improve energy efficiency, such as building energy forecasting (Building Energy Software Tools, n.d.; Bonvini et al., 2014), building temperature control (Lee & Braun, 2008; Ma et al., 2012; Li & Malkawi, 2016), distributed energy system integration (Hajiah & Krarti, 2012; Mulder, Ridder, & Six, 2010), and operation optimization and fault detection (Oldewurtel et al., 2012). Even though these studies have made significant achievements, they focused on only single building and its interactions with distributed systems. Moreover, the benefits from Net-zero building cluster concept have not been fully investigated. A comprehensive review paper introduced and summarized the state of art of building and distributed energy systems studies (Li & Wen, 2014), which also probed the necessities in studying interactions between different buildings, energy systems, and smart grids. The effectiveness of building cluster concept in improving energy efficiency and resilience has been proved in limited number of studies (Lamoudi, Béguery, & Alamir, 2011; Maasoumy et al., 2014; Li, Wen, & Malkawi, 2016; Hu et al., 2012). All these studies, however, use simplified physics based models or data-driven models for operation simulation and control strategy determination. The results from those highly simplified models are difficult to verify against the reality of complex building clusters. Therefore, this study proposes to develop a building cluster emulator that can simulate the operation of multiple buildings and distributed energy systems, and especially device sharing and resources allocation, by using more sophisticated simulation tools to verify and assess the proposed building cluster formation and operation schemes.

Most building energy simulation tools, unfortunately, focus only on single building or single energy system. For example, EnergyPlus (Crawley et al., 2001) is a detailed physics-based whole building simulation program that can simulate the targeted building energy consumption from HVAC, lighting, and other equipment. TRNSYS is another flexible graphics-based software environment used to simulate the behavior of transient systems. There are also several studies focusing on developing distributed energy system models in TRNSYS, such as PV panels models (De Soto, Klein, & Beckman, 2006) and battery models (Kim, 2013). To the best of the authors' knowledge, no simulation tool exists that can simulate the Net-zero building cluster cases proposed in this study. The proposed Net-zero building cluster emulator selects detailed physics-based simulation models for buildings and distributed energy systems in EnergyPlus and TRNSYS. These models are detailed enough to be used to assess the effectiveness of various control strategies, and have been experimentally validated in previous studies. To link all these models together and to enable simultaneous simulation, this emulator uses a Building Controls Virtual Test Bed (BCVTB) developed by LBNL (Wetter & Haves, 2008). After various models are assembled to form a building cluster emulator, a proof-of-concept operation demonstration is then presented. In this demonstration, only two buildings, one ice tank, one PV panel, and one battery are included in this building cluster, but the emulator has the flexibility to integrate more buildings and devices. Section 2 describes the overall structure of this emulator, followed by the detailed information about the module development and connection in Sections 3 and 4. Finally, Section 5 presents testing criteria of the proof-of-concept demonstration and the simulated results.

## 2. Emulator overall design and operation

### 2.1. Emulator design

The overall emulator design and connection are illustrated in Fig. 2. In this emulator, there are four simulation modules: building module, ice tank module, PV-battery module, and operation module. Besides these simulation modules, there is a simulation operation module, which contains a database for simulation conditions and operation strategies, and a simulation result analysis model. The PV-battery module and the ice tank module are shared within this building cluster. EnergyPlus is chosen to simulate the buildings and ice tank thermal storage devices, because it is widely used and validated to provide detailed simulation results at a minimum 1-min time step. TRNSYS is selected to simulate the PV panel power generation and battery system. Operation module, which can provide the control and operation strategies, is present in MATLAB. BCVTB serves as a middleware to connect all the simulation models.

### 2.2. Emulator operation

The emulator will store control and operation schemes in the database and apply them in each module within this cluster through