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Automatic generation and simulation of urban building energy models based on city datasets for city-scale building retrofit analysis

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HIGHLIGHTS

- Developed methods and used data models to integrate city's public building records.
- Shading from neighborhood buildings strongly influences urban building performance.
- A case study demonstrated the workflow, simulation and analysis of building retrofits.
- CityBES retrofit analysis feature provides actionable information for decision making.
- Discussed significance and challenges of urban building energy modeling.

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ABSTRACT

Buildings in cities consume 30–70% of total primary energy, and improving building energy efficiency is one of the key strategies towards sustainable urbanization. Urban building energy models (UBEM) can support city managers to evaluate and prioritize energy conservation measures (ECMs) for investment and the design of incentive and rebate programs. This paper presents the retrofit analysis feature of City Building Energy Saver (CityBES) to automatically generate and simulate UBEM using EnergyPlus based on cities' building datasets and user-selected ECMs. CityBES is a new open web-based tool to support city-scale building energy efficiency strategic plans and programs. The technical details of using CityBES for UBEM generation and simulation are introduced, including the workflow, key assumptions, and major databases. Also presented is a case study that analyzes the potential retrofit energy use and energy cost savings of five individual ECMs and two measure packages for 940 office and retail buildings in six city districts in northeast San Francisco, United States. The results show that: (1) all five measures together can save 23–38% of site energy per building; (2) replacing lighting with light-emitting diode lamps and adding air economizers to existing heating, ventilation and air-conditioning (HVAC) systems are most cost-effective with an average payback of 2.0 and 4.3 years, respectively; and (3) it is not economical to upgrade HVAC systems or replace windows in San Francisco due to the city's mild climate and minimal cooling and heating loads. The CityBES retrofit analysis feature does not require users to have deep knowledge of building systems or technologies for the generation and simulation of building energy models, which helps overcome major technical barriers for city managers and their consultants to adopt UBEM.

1. Introduction

With the increasingly global urbanization, more than half of the world's population lives in urban areas [1]. Many cities have adopted ambitious long-term greenhouse gas (GHG) emission reduction goals. For example, San Francisco (SF) planned to reduce GHG emission 40% below the 1990 level by 2025, and 80% by 2050 [2]. New York City also committed to reducing GHG emission 80% below 1990 level by 2050, with an interim target to reduce 40% by 2030 [3]. The building sector in the United States (U.S.) accounts for about 40% of the total primary energy consumption and GHG emissions [4]. In cities, buildings can consume up to 75% of total primary energy [5]. Buildings in SF

Abbreviations: 3D, Three-Dimensional; AFUE, Annual Fuel Utilization Efficiency; CBES, Commercial Building Energy Saver; CFD, Computational Fluid Dynamic; CityBES, City Building Energy Saver; COP, Coefficient of Performance; CPU, Central Processing Unit; CSV, Comma-Separated Values; ECM, Energy Conservation Measure; ECMs, Energy Conservation Measures; EUI, Energy Use Intensity; FileGDB, File Geodatabase; GHG, Greenhouse Gas; GIS, Geographical Information System; HVAC, Heating Ventilation and Air-Conditioning; LED, Light-Emitting Diode; SCOP, Seasonal Coefficient of Performance; SEER, Seasonal Energy Efficiency Ratio; SF, San Francisco; SHGC, Solar Heat Gain Coefficient; TMY3, Typical Meteorological Year 3; UBEM, Urban Building Energy Models; UMI, Urban Modeling Interface; U.S., United States; VAV, Variable Air Volume

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contribute to 53% of the total GHG emission [6]. Retrofitting the existing building stock to improve energy efficiency and reduce energy use is a key strategy for cities to reduce GHG emissions and mitigate climate change.

Many cities, states, and utilities provide rebates and incentives to support building retrofits [7]. SF Energy Watch program [8], supported by the Pacific Gas and Electric, offers incentives to commercial and multi-family buildings for energy efficiency upgrades to lighting, refrigeration equipment, controls, and network-level computer power management software, etc. SF's Property Assessed Clean Energy financing program [9] helps homeowners finance energy-saving, renewable energy, and water-saving home upgrades. The New York State Energy Research and Development Authority [10] provides financial support for Commercial Real-Time Energy Management system implementation and services for up to 5 years. Florida Public Utilities [11] offers commercial electric rebates for businesses to help offset the cost of making energy-efficiency upgrades to chillers, reflective roofs, air conditioner replacements, etc. Illinois Energy Now [12] Standard Incentive Program provides incentives for common lighting retrofits, variable speed drives for heating, ventilation and air-conditioning (HVAC) equipment, demand-controlled ventilation, boilers, and furnaces. These rebate and incentive programs were designed based on each city's building stock characteristics as well as their climate conditions. It is critical for city managers to have tools to evaluate and prioritize energy conservation measures (ECMs) for their city-scale retrofit analysis, so that they can design the rebate and incentive programs accordingly and effectively.

Data-driven models and physical models are two major methods to analyze energy use for either individual or city-scale buildings. Data-driven models [13,14] can be applied to identify operational problems or predict operational changes. However, it is difficult to predict the retrofit savings of ECMs using data-driven models. On the other hand, physical models of heat and mass flow in and around buildings can be applied to predict operational energy use, as well as indoor and outdoor environmental conditions, to evaluate the retrofit savings for a variety of ECMs. Reinhart and Davila [15] reviewed emerging simulation methods and implementation workflows for bottom-up urban building energy models (UBEM). The basic approach of UBEM is to apply the physical models to groups of buildings.

There are several tools developed to support the generation of UBEM. CitySim (http://citysim.epfl.ch) [16], developed by Ecole Polytechnique Fédérale de Lausanne University, is a tool that allows building energy simulation at the scale of an urban district. Li, et al. [17] introduced a geographical information system (GIS)-based urban building energy modeling system, using the Urban-EPC simulation engine, a modified energy performance calculator engine. Both tools used simplified resistor-capacitor network models to predict the operational energy usage for urban planners to minimize energy and emissions. Fonseca and Schlueter [18] introduced an integrated model for characterization of spatio-temporal building energy consumption patterns in neighborhoods and city districts. The model also used the resistor-capacitor model to predict building heating and cooling loads. Regarding ECM evaluation, the simplified resistor-capacitor network models can estimate savings for simple ECMs, such as replacing inefficient lighting with light-emitting diode (LED) lamps, adding wall insulation, and replacing windows. However, these tools are limited and unable to evaluate complex ECMs that have an integrated effect on multiple building systems, such as replacing HVAC systems, installing daylight sensors and controls, and adding CO_2 sensors for demand-control ventilation. To better evaluate ECMs, detailed physics-based dynamic thermal simulation engines such as EnergyPlus [19] should be used.

Urban Modeling Interface (UMI), developed by Massachusetts Institute of Technology, is a Rhino-based design environment to evaluate the neighborhood density, operational energy use (using EnergyPlus simulation), daylighting, and walkability of neighborhoods and cities [20]. UMI was used to developed UBEM for 83,541 buildings in Boston to estimate citywide hourly energy demands at the building level with the official GIS dataset provided by the Boston Redevelopment Authority and a custom building archetype library of 52 use/age archetypes [21]. After mapping and processing the Boston GIS data sources to create a city building dataset, the modeling workflow required users to create archetypes/prototypes (including envelope, HVAC, internal loads, and operational schedules), import the building footprints using UMI, extrude the building to create a three-dimensional (3D) form using Grasshopper, divide the building into the determined number of floors, add windows according to the building's window-to-wall ratio, and assign the archetypes based on the building type and year of construction. The Boston UBEM modeling workflow requires a significant amount of user effort and knowledge to manually transfer data and generate energy models for the buildings. To better support city managers and their consultants, it is crucial to have a tool that can automate the workflow to generate and simulate the UBEM based on the integrated city building dataset. This required the UBEM tool to have comprehensive archetypes/prototypes covering different building types, vintages, climate zones and to automate the model generation and simulation process. It is important to consider the impact of shading from neighborhood buildings [22–24] on the UBEM energy performance.

This study introduces CityBES (City Building Energy Saver), an open web-based platform that allows users to quickly set up and run UBEM to support city-scale building energy efficiency analysis. In this study, UBEM refers to not only the physical energy models, but also the generation and simulation of those physical models and the storage and visualization of the analysis results. CityBES addressed the limitations mentioned above by using EnergyPlus as the simulation engine, automating the UBEM generation workflow, and considering shadows from neighboring buildings. A case study using CityBES was conducted to analyze the potential retrofit energy and cost savings of five individual ECMs and two ECM packages for 940 office and retail buildings in six city planning districts of northeast San Francisco. The results generated by CityBES were analyzed to evaluate energy savings and cost-effectiveness of individual ECMs as well as ECM packages.

2. CityBES overview

CityBES [25,26] is a web-based platform developed by Lawrence Berkeley National Laboratory (Berkeley Lab) that is freely available to any U.S. city.[1] Fig. 1 shows the key components, data flow, and use cases of CityBES. There are three layers: the data layer, the simulation engine (algorithms) and software tools layer, and the use-cases layer. It provides a 3D visualization with GIS (see Fig. 2) including color-coded simulated site energy use intensity (EUI). The example provided shows site EUI for 940 office and retail buildings in northeast SF. This study introduces the retrofit analysis feature of CityBES, which provides bottom-up physics-based detailed energy modeling of every individual building in a city or district.

CityBES uses the Commercial Building Energy Saver (CBES) Toolkit [27,28], which builds on OpenStudio and EnergyPlus to provide energy retrofit analyses of individual commercial buildings (offices and retail) in U.S. cities. EnergyPlus [19] is an open-source whole building energy simulation program that models both energy consumption (for HVAC, lighting, and plug and process loads) and water use in buildings. OpenStudio [29] provides a software development kit used by CBES to create EnergyPlus models programmatically using Ruby scripts. CBES contains a prototype building database for office and retail buildings for the 16 climate zones (cliamte zone 1B to be added in future) as defined by ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers), and a comprehensive ECM database with cost and

[1] http://citybes.lbl.gov.