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Modeling Boston: A workflow for the efficient generation and maintenance of urban building energy models from existing geospatial datasets

Carlos Cerezo Davila*, Christoph F. Reinhart, Jamie L. Bemis

Sustainable Design Lab, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

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A B S T R A C T

City governments and energy utilities are increasingly focusing on the development of energy efficiency strategies for buildings as a key component in emission reduction plans and energy supply strategies. To support these diverse needs, a new generation of Urban Building Energy Models (UBEM) is currently being developed and validated to estimate citywide hourly energy demands at the building level. However, in order for cities to rely on UBEMs, effective model generation and maintenance workflows are needed based on existing urban data structures.

Within this context, the authors collaborated with the Boston Redevelopment Authority to develop a citywide UBEM based on official GIS datasets and a custom building archetype library. Energy models for 83,541 buildings were generated and assigned one of 52 use/age archetypes, within the CAD modelling environment Rhinoceros3D. The buildings were then simulated using the US DOE EnergyPlus simulation program, and results for buildings of the same archetype were crosschecked against data from the US national energy consumption surveys. A district-level intervention combining photovoltaics with demand side management is presented to demonstrate the ability of UBEM to provide actionable information. Lack of widely available archetype templates and metered energy data, were identified as key barriers within existing workflows that may impede cities from effectively applying UBEM to guide energy policy.

1. Introduction

In response to current global environmental challenges, city governments worldwide have developed ambitious long term greenhouse gas (GHG) emission reduction targets such as 40% and 60% by 2025 (San Francisco and London) or 80% by 2050 in New York City [1]. The City of Boston is no exception and has set emission reduction goals of 25% by 2020 and 80% by 2050 as part of the Greenovate Climate Action Plan [2]. According to this plan, Boston's commercial, residential and transportation sectors account for approximately 50%, 25% and 25% of the city's GHG emissions, highlighting the need for Boston to focus on buildings and their energy supply infrastructure. Indeed, the plan mentions a plethora of building related measures from energy audits and retrofits to the accelerated deployment of renewable energy, district heating and cooling, as well as combined heat and power systems to be applied at the neighborhood and district scales. To initiate and coordinate such a wide range of measures not only requires substantial political consensus and innovative financing mechanisms, but also an intimate technical understanding of how a city's energy ecosystem may change over time as a result of these interventions. For example, as solar panels are increasingly deployed across a city, its typical electricity load curve will change, and with it the economics of auxiliary power plants. To gain an understanding of such interrelated phenomena, city governments and other interested stakeholders require planning tools that provide spatially and temporally defined energy demand data for all buildings, and that facilitate the evaluation of “what if” scenarios to prioritize alternative interventions. Furthermore, such tools need to be based on actively maintained urban databases and practices so they can be effectively implemented.

Urban Building Energy Models (UBEM) have been proposed as an effective urban simulation tool [3], capable both of incorporating existing urban building datasets and mapping a city's energy

* Corresponding author.
E-mail address: ccerezod@mit.edu (C. Cerezo Davila).

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ecosystem. UBEMs are bottom up, physical simulation models of heat flows in and around groups of buildings, which can accurately represent the impact of the urban context on building energy demand. Once calibrated, UBEM capabilities go beyond traditional statistical urban models by estimating the impacts of new technologies and/or policies for which no measured data is available. UBEM models can be combined with mapping techniques in GIS which have been proposed as a data framework for urban energy policy [4,5]. The resulting GIS energy maps can be used to combine and analyze simulated with metered demand, dwelling surveys or building energy labels [6] to support urban decision making.

In addition to GHG emission reduction policies, a UBEM and GIS planning toolset can help municipal governments assessing other kinds of energy urban policies, related to building labeling, fuel poverty or urban energy supply. With the introduction of energy labeling requirements such as Energy Performance Certificates (EPCs) in the European Union (EU) [7], cities have started requiring owners and developers to characterize the efficiency of their properties. The resulting datasets, although valuable for planning purposes, do not cover the whole building stock and their validity is difficult to evaluate. Bottom up energy modeling for building stocks have been proposed as a way to estimate expected certification levels for building types [8,9] and UBEM simulation can help increasing the accuracy of such assessments. Regarding fuel poverty, the problem of energy affordability in low income households has recently become an energy policy driver, especially in the EU, and a significant amount of research has focused on identifying households at risk. This can be done through objective data (EPC databases and proxies) [10] and subjective data [11]. Energy mapping has been proposed as a targeting technique [12] and in that context UBEM simulations can be used to calibrate unknown occupant parameters based on metered data, and in general to better inform such policies. Finally, UBEM models become particularly useful in demand analysis for supply planning purposes, since the impacts of new developments or alternative hourly peaks can be quantified for the design of district systems and local generation [13].

In order to further the development of UBEM as an urban energy planning tool, the authors collaborated with the Boston Redevelopment Authority (BRA) and MIT Lincoln Laboratory (MIT LL) on the development of a building energy demand/supply model for Boston. Using a set of diverse geospatial urban datasets, supplied by the BRA, the authors tested and further developed an automated workflow for the generation and simulation of an UBEM for 83,541 building parcels. The Boston UBEM yields hourly load and fuel use estimates for each building for an entire year. In a related study, these results were later used by MIT LL to develop a series of micro-grid scenarios for various parts of the city [14]. The motivation for the City of Boston to commission this work was to reduce building related carbon emissions, identify economic opportunities and enhance the city's energy resiliency.

2. Research goals

This work is mainly concerned with the workflow used to generate the Boston UBEM, since no model of comparable size had been developed within a municipal government at the time of writing. To ensure that the workflow would be readily replicable in other cities in the US and elsewhere, the authors specifically chose a model generation and simulation procedure that is based on commonly available data sets and state of the art UBEM methods. The main goals of the study are:

- To test the feasibility of generating a citywide UBEM based solely on available public datasets.
- To identify logistic and technical barriers within existing urban data workflows that may prevent cities from setting up and maintaining an UBEM.
- To demonstrate how such model could be used to inform urban energy management policies.

A review of the evolving field of urban building energy modeling is presented in Section 3, followed by a description of the generation method used for the Boston model in Section 4 as well as select simulation results in Section 5. To test its application, an example intervention scenario study for a district in Boston is shown in Section 6. Findings are discussed in Section 7.

3. Urban building energy modeling

To understand spatiotemporal energy demand patterns due to buildings, different types of urban models have been proposed over time, which fall into two main categories: “top-down” or “bottom-up” models [15,16]. Traditional “top-down” building stock models link energy use to macroeconomic variables, such as population trends and economic activity. They serve the purpose of predicting near future energy use by extrapolating from the status quo [17]. They are therefore limited when exploring new technologies or analyzing interventions where energy demands need to be characterized at the scale of the building. “Bottom up” models apply statistical and/or “engineering” analytical methods to represent each building individually. Statistical methods link high level building descriptors such as vintage, usage type and occupancy to measured building energy use via regression models [18]. Statistical models are “robust” since they are based on measured building energy data and thus able to accurately incorporate occupant behavior, which is notoriously difficult to accomplish in analytical models [19]. On the other hand, statistical models based on annual metered data are unable to predict energy use in monthly or hourly time steps or to simulate the combined impact of several energy efficiency measures in buildings. In order to address these two shortcomings of statistical models, a new type of bottom up model called Urban Building Energy Models (UBEM) has been recently introduced.

UBEMs apply simulation methods to represent individual buildings as dynamic thermal models, based on the same heat transfer equations and principles that govern individual building energy models (BEM). At the individual building level, BEM tools are already widely used for the design of high performance buildings [20], code compliance, and certification for rating systems such as LEED [21] in the US and BREEAM [22] in the UK. Being based on the same modeling approach, an UBEM – calibrated against measured energy data – can support complex scenario development. Furthermore, in order to understand the impact of changing hourly load profiles on different energy supply systems, UBEMs can be combined with dedicated energy supply simulation modules [23,24].

While very effective for detailed energy studies, UBEM introduces additional data management and computation requirements vis-à-vis BEM. Since models need to be generated and simulated for potentially thousands of buildings, conventional BEM approaches become unacceptably resource intensive, and impossible to manage. Therefore, in order to make UBEM an effective tool for standard real world applications, a reconceptualization and automation of individual building energy model workflows is required. As documented in a recent review paper by the authors, a host of new methods had to be developed over the past decade to assemble and manage the enormous amount of data required to generate and ran an UBEM within a reasonable time frame [3]. Most of these methods share certain common traits such as the modeling