Energy & Buildings 173 (2018) 103–116

Contents lists available at ScienceDirect

Energy & Buildings

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

A comparison of two modeling approaches for establishing and implementing energy use reduction targets for a university campus

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ARTICLE INFO

Article history:
Received 22 October 2017
Revised 26 March 2018
Accepted 20 May 2018
Available online 27 May 2018

ABSTRACT

To reduce global greenhouse gas emissions associated with building energy use, owners of large building portfolios such as university campuses frequently rely on building energy models (BEM) to better understand potential costs and benefits of retrofits. Model development workflows that are designed for individual buildings require a level of effort that would be time and cost prohibitive to apply to such campuses which often include hundreds of diverse-use buildings. While smaller campuses can effectively utilize the traditional BEM approach to study retrofit scenarios, this option is therefore not feasible for larger campuses. Large universities have instead utilized a combination of statistical and spreadsheet models which may not fully capture the unique architectural features, programmatic requirements, and systems configurations of individual campus buildings. With the goal of overcoming these limitations, two separate urban energy models, that employed considerably different methodologies, were developed for the campus of the Massachusetts Institute of Technology to evaluate future energy scenarios with an appreciably smaller effort vis-à-vis developing building-by-building energy models. This study reviews these two models with regards to their setup and calibration effort, ability to model individual building energy use, and the accuracy in predicted savings from implementing a variety of retrofitting measures. The paper identifies both models' strengths and limitations and suggests best practice procedures for administrators of other campuses interested in undergoing a similar exercise.

1. Introduction

Building energy use has long been identified as a key contributor to global greenhouse gas emissions [1] and energy efficiency retrofits to existing buildings constitute a significant opportunity to reduce these emissions [2]. To facilitate this process, energy policies at the federal and municipal level have traditionally focused on implementing a range of energy saving measures in individual buildings to realize reductions in energy use [e.g., 3,4]. For larger, especially commercial and institutional buildings, owners frequently rely on a simulation-based assessment of a retrofit strategy to better understand potential costs and benefits, which may vary significantly from building to building. This type of analysis is based on well-established and standardized whole building energy modeling (BEM) programs [5] that simulate heat and mass flows in and around buildings, and calculate energy use for different end-uses required to meet programmatic requirements and occupant comfort criteria. The process typically involves developing a BEM which accepts the building's existing envelope, electrical and mechanical systems characteristics as inputs. Once the model is developed and its predicted energy use matches closely with measured existing energy use, it is utilized to simulate the energy effects of a wide range of retrofit scenarios by modifying the relevant input parameters. While smaller university campuses have utilized the traditional BEM approach to study retrofit scenarios [e.g., 6,7], given the considerable time and effort required to collect data and setup an energy model for even a single building [8,9], this option is not feasible for larger university campuses with hundreds of buildings.

Over the past five years, a new genre of urban building energy models (UBEM) [10] has been developed. These bottom-up engineering methods apply BEM concepts to a large number of buildings at a neighborhood, or even a city scale [11]. To do so, UBEMs divide a given building stock into archetypes, and assign the same construction standards, usage patterns, and mechanical and electrical system parameters to all buildings within an archetype. Once calibrated to measured energy use of a subset of buildings, UBEMs have been shown to successfully project total annual energy use of residential neighborhoods [12]; and, in combination with sta-

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https://doi.org/10.1016/j.enbuild.2018.05.035
0378-7788/

tistical approaches such as Bayesian methods, even simulate the diversity of annual and monthly energy uses of buildings within an archetype [13]. Utilities or municipalities, therefore, can directly employ UBEMs when interested in identifying a strategic mix of retrofitting measures across a residential building stock [e.g., 14].

In contrast to residential neighborhoods, large university campuses exhibit unique qualities: they are long-term owner-occupied, and their owners often have a societal obligation to commit towards a low carbon economy. Established university campuses typically have aging buildings in their portfolio, which are in dire need of renovation [15], along with a limited budget to implement retrofit strategies. They also include buildings with high diversity uses, ranging from classrooms and laboratories to student dorms, restaurant, shopping and sport facilities, which cannot be easily classified into predominant programmatic archetypes. As a result, university administrations typically require a building-by-building prioritization plan with a high degree of certainty in expected energy cost or carbon emission reductions in return for their investment, while also considering other concerns such as safety, programmatic needs, future growth etc. For such large campus projects, where each building needs to be evaluated individually, traditional UBEM approaches do not offer suitable solutions to formulate cost-effective carbon reduction strategies.

Large campuses have instead relied on a combination of statistical [16] and spreadsheet tools [17] to benchmark the current energy use and greenhouse gas emissions at the campus scale. Such studies have established the existing campus conditions successfully [18], effectively compared campus energy use and greenhouse gas emissions with other institutions [19], and evaluated high level upgrade scenarios at the campus scale [20]; but are limited in their ability to assess opportunities or simulate future scenarios, especially for individual buildings. For building level assessments, campuses conduct detailed surveys of the architectural features and operational characteristics of a few buildings [e.g., 21] to develop energy models that can simulate retrofit scenarios. While such studies identify the opportunities for energy savings, their findings are limited only to these few specific buildings.

To extrapolate results from simplified analyses and provide data for evaluating potential strategies across all campus buildings, other studies have employed cluster analysis techniques to determine load features of different building groups [22], normalized energy consumption based on site weather information [23] and developed reduced order energy models defined by a few influential input variables [24,25]. These models are based on the premise that the complex nature of building energy use renders the calibration of numerous building energy models time and effort intensive, and do not fully capture the unique architectural features, programmatic requirements, or the electrical and mechanical systems configurations of individual campus buildings. As a result, without details of individual building performance characteristics, these models are able to provide general guidance across multiple buildings, but are unable to assess future scenarios at an individual building or a partial retrofit scale.

Recent papers have presented web-based platforms [26], and software [27] designed to allow users to quickly set up and run urban energy models [e.g., 28] that analyze the energy demand of individual buildings and can also evaluate alternate scenarios. These models overcome the complexity of generating numerous individual building models by automatically drawing information from available city-wide datasets, but do not fully address the model calibration process which requires extensive data collection to determine the physical and operational characteristics of existing buildings. The development of automated building energy model calibration workflows, with the goal of computationally estimating the unknown characteristics of a building based on some known building properties and measured energy use information, has been a research subject in recent years. Studies have proposed employing brute-force sampling [29], graphical pattern recognition [30], and global optimization algorithms [31] to iteratively adjust the values of unknown parameters until the difference between measured and simulated data is minimized. While these techniques aim to reduce the high time and cost expense associated with experienced auditors and modelers working through the calibration process, they still require a considerable computational expense associated with running hundreds of thousands of energy simulations on super-computers, making these techniques unfeasible for most users.

To work towards the ideal urban model for a campus that provides the fidelity of information that a collection of individual calibrated BEMs would yield while requiring the same effort as to build an UBEM, two models were recently developed for the campus of the Massachusetts Institute of Technology (MIT), one based on a *spreadsheet* approach with select BEMs in the background, the second as an archetype based *UBEM*. The purpose of this manuscript is to review these two models with regards to their setup and calibration effort, ability to model current individual building energy use vis-à-vis measured data as well as predicted savings from implementing a variety of retrofitting measures. The objectives are to identify both models' strengths and weaknesses and to suggest best practice procedures for administrators of other campuses interested in undergoing a similar exercise.

2. Methodology

The Office of Sustainability at MIT, in response to the City of Cambridge's Net Zero Action Plan [32], recently completed a feasibility study for potential upgrades to existing campus buildings [33]. Two separate models were developed in parallel, the first by the environmental design consulting firm Atelier Ten which utilizes a combination of statistical techniques that attribute energy use to the primary programmatic uses on campus before evaluating the effect of energy efficiency measures for those specific program types; and the second by the Sustainable Design Lab at MIT as a bottom up, urban building energy model (UBEM) designed to forecast the impact of building-by-building retrofit scenarios. The following sub-sections describe these two approaches in detail, with regards to the model inputs and the underlying development procedures. The next section compares and contrasts the results from these two models for baseline conditions as well as potential retrofit scenarios at campus and individual building levels.

The MIT campus in Cambridge, Massachusetts, is located on 168 acres (68 ha) of land that spans approximately one mile (1.6 km) along the north side of Charles River basin opposite the predominantly urban Back Bay neighborhood of Boston, Massachusetts. MIT's overall building portfolio consists of a total floor area of approximately 1.2 million square meters. The focus of both the studies is a stock of one-hundred MIT owned and maintained buildings that constitute just over one million square meters of academic, laboratory, residential, and ancillary spaces. The available dataset, comprising of metered utility use and program area distributions for each building, was used to develop the aforementioned spreadsheet and the UBEM campus models, which are further described below.

2.1. Model inputs

Each building on the MIT campus is broadly classified as academic, laboratory, ancillary or residential, based on the predominant programmatic use. In addition, detailed floor area compositions with fifteen detailed functional uses have also been compiled for most buildings. As an example, Table 1 presents a sample of