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Synergizing disparate component-level energy resources into a single whole building tool to support energy conservation action in small commercial buildings

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ABSTRACT

Small commercial buildings represent 94% of U.S. commercial buildings by number and consume approximately 9% of national total primary energy. However, advancements in building efficiency technologies have focused on large commercial building systems, while these buildings also have the financial support and personnel resources to invest in implementing improvements. Pragmatic and easy to use tools to assist small commercial building stakeholders in making informed and effective energy decisions are scarcely available. One approach is to synergize existing research and resources into a single package. This research presents the development of a building energy assessment resource (BEAR) and implementation in thirteen buildings. BEAR performed similarly and favorably in estimating tenants' total energy consumption across all three enterprise types: food service, retail and office. Results reveal a weighted average absolute difference between BEAR and utility bills of 4.7% for electricity and 13.3% for natural gas estimation. Potential factors impacting BEAR's accuracy include assumptions made for modal parameters, e.g. power and time in mode, in addition to fuel flow rate controls in commercial cooking equipment. Discussions on the broader implications of the developed energy resource include applicability across small commercial enterprise sectors and future advancements directed towards policy makers and energy service providers.

1. Introduction

Efforts to combat global dilemmas posed by anthropogenic environmental degradation have partially taken shape around building energy efficiency. While advances in building energy use have been made for large commercial buildings, efforts in small commercial buildings (SCBs) have been lacking. Yet in the U.S., SCBs (under 4645 m^2 in floor area) represent 94% of commercial buildings by number and approximately 9% of national primary energy consumption U.S. EIA [1]. Moreover, 13% of global annual primary energy is consumed by small and medium sized enterprises, constituting the majority share of SCB occupants [2].

Support for SCBs has slowly risen from governments, non-profit organizations, and research [3–5]. The passage of the Energy Efficiency Improvement Act of 2015 [3] tasked the U.S. EPA with developing a *Tenant Star* program intended to address energy efficiency of individual building spaces while engaging both enterprises and building owners. The Berkeley Lab, in partnership with Architecture 2030, developed a small commercial whole-building toolkit, aiming to provide energy profiles and energy efficiency improvements to participating partners [4]. Additionally, research performed by Barnes and Parrish [5] developed a library of building case studies intended to provide guidance to energy conservation programs on specific key barriers to adoption, widely observed throughout the SCB sector.

While these aforementioned efforts are increasing awareness and providing technical support, additional efforts are needed to advance energy efficiency in this critical building sector. Complex and heterogeneous, the U.S. Energy Information Administration (EIA) defines sixteen commercial activities each presenting barriers to energy efficient technologies and practices in SCBs. Commonly experienced barriers include *a lack of access to information* and *limited access to capital* [5–7]. In part, this research attempted to directly address the informational barrier and indirectly address SCBs' limited access to capital through development of our publicly available resource to effectively focus SCB investments.

Abbreviations: BEAR, Building energy assessment resource; SCB, Small commercial buildings; AElC, Annual electric consumption; ANgC, Annual natural gas consumption; AUHr, Annual usage hours.

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In our prior work, we observed that many disparate calculators and methods existed for building energy efficiency efforts [8]. For example, EnergyStar and the U.S. Department of Energy (DOE) have made public a portfolio of energy efficiency calculators for residential and commercial components, defined for the purpose of this paper as any appliance, equipment or building element that consumes electricity, natural gas, or other fuel [9,10], while national laboratories offer other sources of energy information [11–13]. However, we argue that one overarching resource is needed to serve the small building sector. In response, we developed the *Building Energy Assessment Resource* (BEAR). Our aim was to synthesize existing disparate energy quantification methods and resources into one package, with the ultimate goal of reducing energy consumption in the small commercial building sector.

Drawing upon existing research, BEAR is intended as an informative energy resource, accessible to small building owners and tenants and operational with minimal parameter inputs [8,14]. The design objectives of BEAR include *accuracy* (i.e. the difference between BEAR energy estimates and energy bills), *robustness* (i.e. the ability to be used in the portfolio of building activities), and *practicality* (i.e. can be used by building stakeholders). This article will evaluate if BEAR achieves the first three design objectives through implementation in thirteen SCBs.

A review of measurement-based energy quantification methods provides context to our use of bottom-up energy disaggregation to create BEAR. The remainder of the article is organized as follows. Section 3 presents the development of methods underpinning the six steps for using BEAR. Section 4 summarizes the thirteen buildings a part of the case study. Section 5 presents results and discussion of the design objectives of BEAR in estimating tenants' annual energy consumption in relation to collected energy bills. Lastly, findings and future advancements of BEAR are discussed.

2. Background of energy quantification and disaggregation methods

One approach to stimulate energy efficiency investments is to provide informative energy evaluation resources to building stakeholders. For the purpose of this article an *energy evaluation resource* is a resource that enables the assessment of energy use in a building or space by providing detailed energy use information. The energy quantification method – the method used within an energy evaluation resource to quantify energy use at varying levels (e.g. building, tenant, or appliance) – is the driving force of resource performance. Energy quantification methods may be categorized into three types: calculation-based, measurement-based, and a hybrid of the two [15]. Employing a *fit-for-purpose* approach, where the ideal design is the least complex while meeting desired goals, this research identified measurement-based bottom-up energy bill disaggregation as the best fit energy quantification method. The following review presents the current state of *bottom-up* energy bill disaggregation, and a brief review of two commercial-specific whole-building energy disaggregation resources.

2.1. Energy bill disaggregation methods

Energy bill disaggregation is the process of dissecting whole building energy consumption into major end-uses through use of *disaggregation algorithms* or *disaggregation estimations* [15]. Disaggregation algorithms apply understanding of relationships between an energy system and the underlying determinants for energy consumption (e.g., space heating and heating degree days); while disaggregation estimations apply knowledge of energy consumption for individual systems (e.g. rated power and hourly use of a computer monitor). *Bottom-up* energy bill disaggregation employs both disaggregation algorithms and estimations.

A bottom-up approach compiles power demand and operational hours of appliances to determine energy consumption using estimation algorithms, prior to reconciling with energy bills [16–19]. Lee, Yik and Burnett [20] defined an estimation algorithm for quantifying appliance electricity consumption, based on equipment numbers, rated power demand, and hours in operation. Using their estimation algorithm, it is also possible to estimate electricity consumption for plug-load and lighting end-uses, before reconciliation with energy bill data to obtain cooling energy consumption.

Bottom-up energy disaggregation approaches provide high granularity of energy consumption, enabling the provision of targeted recommendations for improving energy efficiency. Moreover, collected appliance-level data organized into a publicly available database is considered a highly useful resource to consumers, research, and policy makers [21,22].

The bottom-up approach does have disadvantages predominantly in the form of time requirements to catalogue appliances. Practitioners of bottom-up methods collect an inventory of appliances and equipment in a building, which can take several hours for a building under 465 m^2. As one moves up the SCB size range towards a 4,645 m^2 building, the time investment grows [23]. However, development of an appliance-level database especially at a national level would help to reduce these commitments.

2.2. Existing whole building energy disaggregation resources

Approaches taken to provide the SCB sector with detailed energy information include the Building Energy Asset Score and Small Commercial Toolkit [24,25]. The U.S. DOE and Pacific Northwest National Laboratory (PNNL) released the Building Energy Asset Score with a user-interface and EnergyPlus modeling software for whole building energy analysis [24,26]. This program ranks a building's energy efficiency based on user-input energy assets (e.g. HVAC, lighting, water heating, and design characteristics), comparing with other similar buildings. The tool enables users to model their building by inputting operational and physical constraints, while outputting building performance metrics and recommendations for energy improvements. However, the tool has shortcomings in addressing the complete portfolio of building activities in SCBs. The Building Energy Asset Scoring Tool accounts for office, retail and other similar building use types, but omits food service and food sales, which are the two most energy intensive building uses in small commercial buildings [1].

Another resource developed by the Berkley Lab in partnership with the Architecture 2030 Challenge [4] is the Small Commercial Toolkit package. This resource includes a set of technical tools and programs for analyzing energy consumption [25]. The Small Commercial Toolkit been made publicly available (cbes.lbl.gov/buildings).

In reviewing the literature, we propose the development and implementation of a bottom-up energy bill disaggregation resource that fits the needs of SCB stakeholders. Further, examination of existing energy disaggregation resources revealed limitations in quantifying commercial cooking [27,28]. BEAR aims to address limited access to information in the food service sector.

3. Methods

In developing the building energy assessment resource, we drew from key research on fit-for-purpose design (i.e. least level of complexity to meet a desired outcome) [29] in coordination with three guiding criteria as proposed by van Dijk, Spiekman and de Wilde [30]: transparency, reproducibility, and robustness. The design objectives include accuracy, robustness, and practicality. This