Energy and Buildings 107 (2015) 407–416

Contents lists available at ScienceDirect

Energy and Buildings

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

Building energy retrofits under capital constraints and greenhouse gas pricing scenarios

Matthew Dahlhausen*, Mohammad Heidarinejad, Jelena Srebric

Department of Mechanical Engineering, University of Maryland, College Park, MD, USA

ARTICLE INFO

Article history:
Received 4 March 2015
Received in revised form 10 August 2015
Accepted 22 August 2015
Available online 24 August 2015

Keywords:
Office buildings
Energy retrofits
Energy efficiency measures
Simple payback
Integrative design
Retrofit measure packages
Energy simulations
Greenhouse gas pricing

ABSTRACT

This study demonstrates that capital availability needs to be considered while developing retrofit measures. Specifically, this study established a methodology using building energy simulations to determine optimal retrofit options over a range of NIST greenhouse gas pricing projections, full and half-price measure costs, and capital availability ranging from \$1/ft^2-yr (\$10.76/m^2-yr) to \$100/ft^2-yr (\$1076.39/m^2-yr), representing no capital constraint. The demonstration considers a sub-metered office building in Philadelphia with central heating and cooling equipment nearing replacement. When capital is restrained, measure installation occurs over several years, reducing energy and cost savings over the investment lifetime. This effect is as significant as the greenhouse gas price. Furthermore, changing measure installation order matters most when capital availability is constrained to \$1/ft^2 (\$10.76/m^2), resulting in a difference of \$0.34–0.43/ft^2 (\$3.66–4.63/m^2) between the least-optimal and optimal measure ordering. All but \$0.05/ft^2 (\$0.54/m^2) of this difference is explained by when fast-payback measures are installed; load-reduction benefits were insufficient to justify delaying fast-payback measures. This suggests that capital availability is a determinant of retrofit financial performance, and ordering measures for optimal load reduction is inferior to ordering measures with fast-payback when these strategies conflict. Therefore, increasing investment in energy retrofits is key to reducing greenhouse gas emissions.

1. Introduction

Governments and institutions are focusing on building energy efficiency as an area for sizable, cost-effective energy use reduction and greenhouse gas mitigation [1,2]. Commercial buildings are important to consider, as they are capital intensive and long-lasting, with a median lifetime of 70 years [3]. Without considerable efforts to retrofit the current building stock for energy efficiency, as much as 80% of 2005 thermal energy consumption can remain past 2050 [4]. Currently, while 86% of construction costs go to building renovation, little of that goes to improving the energy efficiency of buildings [5]. Renovation rates are around 2.2%, with an 11% average energy savings [6]. This rate needs to grow several-fold, with average savings around 55%, to approach modest emission reduction targets and Architecture 2030 goals [6]. Few renovation projects in the U.S. have achieved this savings level, with one recent study identifying only 50 such projects, known as deep or advanced energy retrofits [7,8]. The lack of major deep or advanced retrofit projects suggest that it is necessary to consider the influence of major setbacks in the building retrofit market, such as the limited annual retrofit budget or capital constraints, when a project is in the process of decision making with respect to building retrofit options.

Lack of access to capital, insufficient payback, and energy savings uncertainty are top barriers to making energy retrofits more prevalent [9,10]. Most projects are funded with limited internal capital, sometimes with assistance from grants, rebates, and other incentives. These projects have tended toward individual lighting, controls, and Heating, Ventilating, and Air Conditioning (HVAC) equipment measures with reliable savings, as it can be very expensive to go through an extensive energy audit that may not significantly reduce the energy savings uncertainty. While the practice of single measure ranking by simple-payback results in good financial payback on a per-measure basis, it does not take advantage of measure integration that can yield greater energy savings. Most notably, heating and cooling load reduction measures enable downsizing central mechanical equipment for significant replacement cost savings. This means that choosing measure with optimal payback individually may not yield the optimal retrofit decision. Overall, uncertainty and capital budgets make energy retrofits an economic problem, not just a physical one.

Several studies investigated and established methodologies for choosing energy retrofits, summarized in the literature [11].

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* Corresponding author.
E-mail address: mdahl14@umd.edu (M. Dahlhausen).

http://dx.doi.org/10.1016/j.enbuild.2015.08.046
0378-7788/

A subset of the retrofit literature considers the integrative aspect of measure selection. A study showed performance of measure packages with uncertainty of technology performance, capital costs, energy prices, carbon tariffs, and grid decarbonization [12]. This study also evaluated the range of outcomes under three decision criteria: (maximum weighted average of options, maximum under the most pessimistic scenario, and the smallest regret to minimize difference in expected outcome. This approach captures the interactions among retrofit measures, and found that technology performance, capital costs, and energy prices caused the most significant difference in financial performance. This study implemented all measures at once, which is not always feasible, depending on available capital. Another study demostrated a process to implement measures in a package ordered depending on capital availability [13]. This approach reduced financial risk exposure of a large retrofit project by staying within an internal budget, but it did not consider what measure package would result in the optimal savings. Both of the approaches, measure integration and packaging, are important. Interestingly, extending the project timeline incorporates major equipment replacements that are already embedded in capital plans into a comprehensive retrofit package. This allows targeted load reductions to precede equipment replacement, and to account for the cost of waiting. There is a trade-off between sacrificing expected life of equipment by replacing it now with other measures, or waiting until end-of-life and forgoing possible energy savings from implementing measures sooner.

This study established a methodology for evaluating the impacts of (1) the capital cost constrains, (2) uncertainty associated with measure costs, (3) future energy and carbon tax escalation on the retrofit decision making. The methodology was demonstrated for a case study of an actual building with sub-metered energy data including interval data for different end-uses deployed to calibrate a baseline building energy model. The calibrated model enabled considerations of different retrofit scenarios to include intrinsic and extrinsic uncertainties associated with the decision making for a building retrofit. Furthermore, this study also developed software for interoperability with OpenStudio [14,15] based on R scripts [16], allowing deployment of the methodology to retrofit decision making for many buildings. Finally, the case study for an office building in Philadelphia, PA, demonstrated the significance of the difference in capital availability to the optimal retrofit measures.

2. Methodology

Energy retrofit measure selection is dependent on capital availability, financial criteria, and uncertainties in energy savings and energy costs. Including measure interactions and savings uncertainties is necessary to properly account for a measure's impact on overall building performance. This measure integration and packaging increases the number of options to consider, and requires energy simulations to handle the complexity of measure interactions. Installing measures longitudinally based on a fixed capital budget adds further complexity, as the order in which measures are installed becomes significant. Load reduction measures allow equipment downsizing, and there is a performance difference for different sized systems with the same energy efficiency measures. This consideration greatly increases the number of energy simulations. Fig. 1 shows the analysis process of all the possible retrofit path-options, including the downsizing difference, under capital constrains to calculate their impact on the optimal retrofit measure option. As indicated in the figure, the established methodology comprises of five steps including (1) develop a calibrated energy model, (2) Select energy efficiency measures (EEMs), (3) generate unique simulations for measure combinations, (4) run building energy simulations, (5) analyze retrofit path options for different financial scenarios, and identify optimal options. The code to demonstrate this methodology for the case study presented in this paper is available on Github, a web-based code repository [17].

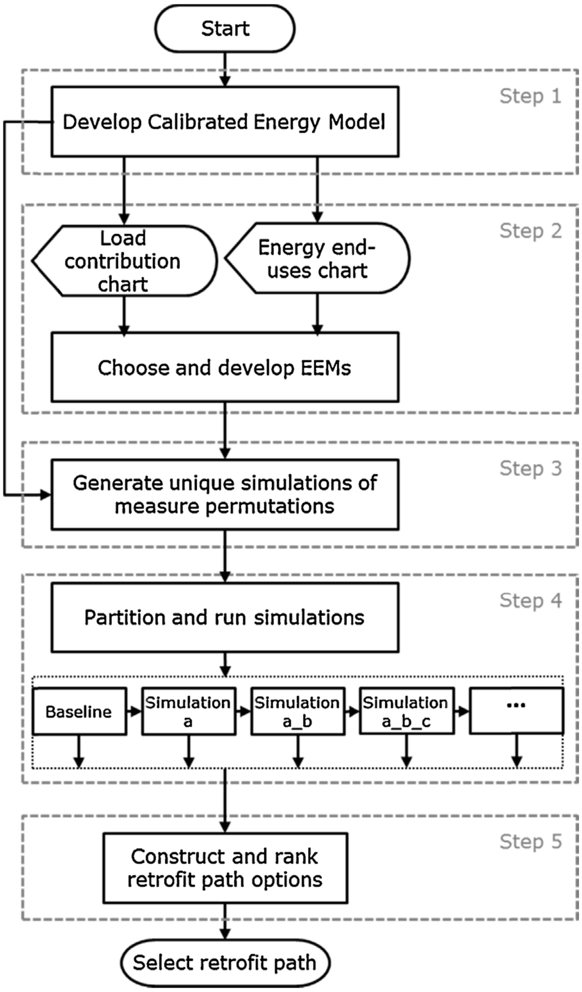

Fig. 1. The flowchart of established methodology for retrofit decision making.

2.1. Develop a calibrated energy model (Step 1)

The first step in the evaluation of different EEMs using building energy simulation tools requires developing a calibrated baseline building energy model. The calibrated baseline energy model needs to meet the requirements of the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) Guideline 14 2002 [18]. Most commonly deployed calibration of the building energy model uses monthly electricity and gas consumption from the utility bills due to their ubiquitous availability [19]. However, if sub-metered interval data for a building are available, a more accurate calibration method uses the sub-metered interval data to calibrate the building energy model with the 15 min sub-metered building energy data [20,21]. This study uses 15 min sub-metered energy end-uses interval data for the calibration of the baseline building energy model.

2.2. Select energy efficiency measures (Step 2)

The selection of EEMs depends on the building principal functionality, age, size, and financial constraints. Use of the building energy simulations allows identification of energy end-use breakdown, main load contributions, and measures that will most likely