



# Calibration of building energy models for retrofit analysis under uncertainty

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## ABSTRACT

Retrofitting existing buildings is urgent given the increasing need to improve the energy efficiency of the existing building stock. This paper presents a scalable, probabilistic methodology that can support large scale investments in energy retrofit of buildings while accounting for uncertainty. The methodology is based on Bayesian calibration of normative energy models. Based on CEN-ISO standards, normative energy models are light-weight, quasi-steady state formulations of heat balance equations, which makes them appropriate for modeling large sets of buildings efficiently. Calibration of these models enables improved representation of the actual buildings and quantification of uncertainties associated with model parameters. In addition, the calibrated models can incorporate additional uncertainties coming from retrofit interventions to generate probabilistic predictions of retrofit performance. Probabilistic outputs can be straightforwardly translated to quantify risks of under-performance associated with retrofit interventions. A case study demonstrates that the proposed methodology with the use of normative models can correctly evaluate energy retrofit options and support risk conscious decision-making by explicitly inspecting risks associated with each retrofit option.

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## 1. Introduction

In the US and UK, existing buildings account for 39% of the total energy demand [1,2]. While the energy consumption of current buildings is projected to grow annually by 1.7% to 2025 [3], the total floor area of buildings is projected to increase roughly at the rate of 1–2% per year [4]. It is indeed well-accepted that existing buildings will have a critical role in meeting energy and emission reduction targets in developed countries. Mills et al. [5,6], has shown that improving existing buildings will yield median energy savings of 16% in the United States. Furthermore, the study projected that if these median energy savings are applied to the US commercial building stock, potential energy-savings will correspond to monetary savings of approximately \$30 billion by 2030. According to this projection, energy retrofits of existing buildings can play a significant role in achieving national energy reduction targets cost-effectively.

Energy retrofits of existing buildings are important because buildings tend to undergo system degradation, change in use, and unexpected faults over time. It is well known that the efficiency of buildings and their equipment degrades over their service life, and even faster when they are not maintained appropriately. Building components can also under-perform when they are not properly

designed or installed. Faults in mechanical systems and lighting equipment alone can account for 2–11% of the total energy consumption for commercial buildings [7]. A meta-analysis of 643 commercial buildings by the Lawrence Berkeley National Laboratory also illustrates the wide variety of problems associated with mechanical equipment, lighting systems, and building envelopes of existing buildings [5,6].

Indeed, owing to the importance of energy retrofits of existing buildings, governments at different levels are investing in policies and initiatives related to improving the efficiency of existing buildings. In the United States, President Obama launched “Better Buildings Initiative” to reduce energy consumption of commercial buildings by 20% by 2020 through cost-effective retrofit interventions [8]. At the federal government level, the U.S. Department of Energy selected 25 innovative projects across the country under the Retrofit Ramp-Up Initiative to support whole-neighborhood building energy retrofits [9,10]. At the city level, the city of Chicago initiated a Chicago Climate Action Plan that targets to retrofit 50% of existing commercial and residential buildings in Chicago for 30% energy reduction by 2020 [11]. Across the pond, in the UK, the government’s aim to reduce its carbon emissions by at least 80% by 2050 will require more effort than maintaining stable overall levels of consumption over the years. The Carbon Trust asserts this view in CTC766 [12], requiring all existing commercial buildings to achieve at least an F-rated energy performance certificate by 2020 (most existing commercial buildings are currently G-rated). Recent policies such as the Carbon Reduction Commitment (CRC) scheme,

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energy certificates, climate change levy & agreements (CCL), the renewable heat incentive (RHI), and upcoming 'Green Deal' are likewise designed to incentivize commercial building owners to invest in energy efficient retrofits.

The main aim of an energy retrofit is to improve energy efficiency by implementing the most optimal mix of technologies at a reasonable investment. In practice, it has become mainstream to use building simulation software to quantify expected energy savings from retrofit technologies where possible. However, building simulation software are more suitable for predicting energy use of yet-to-be-built projects, in which properties of the building and its systems parameters can be assumed to follow engineering design specifications. Existing buildings come with nuances associated with how buildings and their components are actually operated and these are often difficult to represent in building energy models. Thus, the energy savings output from simulation models of existing buildings need verification and/or calibration. It is in response to this gap that most Energy Service Companies (ESCOs) rely on the International Performance Measurement and Verification Protocol (IPMVP) [13] for best practice techniques to verify their estimates of energy savings from energy efficiency, water efficiency, and renewable energy projects and to allocate risks appropriately.

Allocation of risks requires uncertainty quantification of projected cost effectiveness of technology options for a given retrofit project. The importance of assessing if certain energy retrofits will be less or most cost effective is critical in context of the ESCOs industry [14–16]. ESCOs undertake retrofits of existing buildings through performance based contracts that typically guarantee savings as part of their service. The expression of a guarantee allows building owners to invest in the retrofits with high confidence, but the structure leads to relatively safe and often less aggressive ambitions towards energy savings. This is due to the fact that ESCOs rely on experts' knowledge and previous successes to estimate investment paybacks of technology choices for building retrofits. An experts' subjective judgement cannot always correctly estimate the uncertainties associated with a combination of technology options. As a result, ESCOs are not likely to invest in high-impact, high-cost technologies, unless the probability of energy savings can be quantified appropriately and associated risks expressed such that comparison between competing technologies is explicit. Yet, there is lack of sufficient research in developing methods that are able to support risk analysis of investment decisions in energy upgrades of buildings.

This paper presents a scalable, probabilistic methodology that can support investments in energy retrofit of buildings while accounting for uncertainty. The methodology is based on Bayesian calibration of normative energy models. Based on CEN-ISO standards, normative energy models are light-weight, quasi-steady state formulations of heat balance equations, which makes them appropriate for modeling large sets of buildings efficiently. Calibration of these models enables improved representation of the actual buildings and quantification of uncertainties associated with model parameters. In addition, the calibrated models can incorporate additional uncertainties associated with retrofit technologies to generate probabilistic predictions of energy savings which can be naturally translated to risks associated with the investment.

## 2. Energy models of existing buildings

Energy simulation models play a key role in computing potential energy savings from retrofits. In order to reliably predict energy-savings from a set of proposed retrofit technologies, the simulation model must represent a building as operated; that is, the model should capture the building systems as-installed, as-operated, and as-used. Hence, building audits and monitored energy consumption also become integral to the modeling process. If the baseline model can generate outcomes that closely match monitored energy

consumption of a building, then it is more likely to predict reliable estimates of energy-saving from planned retrofit options for that building. To get a good match between outcomes of the baseline model and monitored energy consumption, the analyst or the modeler calibrates the parameters of a simulation model to match their actual counterparts in the building. This is a widely accepted modeling approach for analyzing existing buildings [17–19]. Model parameters can be calibrated to an extent through building audits – at least for those parameters that are physically observable. For non-observable parameters (which can be quite numerous depending on the fidelity of the analysis model), one counts on an expert's knowledge and experience.

In this paper we use the term *operational adjustments* to refer to the process of auditing a building to determine appropriate values for the observable parameters of a building simulation model. It typically includes site visits, interviews with building managers, field measurements to determine physical properties of the building (such as geometry, location of blinds, installed systems, etc.), occupancy patterns, plug loads, and control settings. This is an important part of the calibration process since the actual building operation often deviates from specifications assumed and documented during design and construction. The term *parameter estimation* is used to define the process of setting values for the non-observable simulation parameters. Most simulation exercises on retrofit analysis employ a heuristic method for the parameter estimation process: The expert selects a set of parameters that are likely to influence the outputs of the simulation model most, and are also likely to require adjustments on a building-to-building basis. He/she then sets the most appropriate combination of values for those parameters by running the simulation model iteratively with different parameter values until differences between computed and actual energy use are reasonably small. Indeed, although the calibration process is manual, it essentially resembles deterministic optimization, resulting in an optimum set of parameter values to be used for exercising the simulation model for retrofit analysis.

Thus, building a reliable model of an existing building asks for a fundamentally different approach than simulating the behavior of a building that is yet to be constructed. The former is essentially an empirical exercise that relies on good observations to infer values of model parameters, and the latter is based on embodying the physics of the important components of the proposed building to appropriate level of fidelity so that the overall model is a good enough representation of its main sub-systems and their interactions. For both cases, high fidelity and high resolution models are generally accepted as more reliable in the simulation community. Indeed, most practices tend to use dynamic or transient simulation models for analyzing buildings – especially when a single building is in focus.

Many inefficiencies can be noted in the modelling approach for building retrofits: First, the quality of the model relies heavily on the subjective judgment of an expert; Second, identifying a single combination of parameter values that result in a good fit between monitored and computed energy consumption does not guarantee that the parameter values represent reality. Despite being quite labor intensive and time consuming, the process does not derive a set of parameter values which can be used to evaluate relative cost-benefits of different retrofit options with confidence. Most importantly though, uncertainties regarding parameter values always exist in any model, and are left unquantified even after being considered during the parameter estimation process. If uncertainties in parameter values are not quantified, one cannot compute their cumulative impact on the reliability of the model outputs. We thus argue for improving the parameter estimation step substantially by using statistical inference. We propose and demonstrate a model calibration process based on a Bayesian

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