Towards a Very Low Energy Building Stock: Modeling the US Commercial Building Sector to Support Policy and Innovation Planning

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This paper describes the origin, structure and continuing development of a model of time varying energy consumption in the US commercial building stock. The model is based on a flexible structure that disaggregates the stock into various categories (e.g. by building type, climate, vintage and life-cycle stage) and assigns attributes to each of these (e.g. floor area and energy use intensity by fuel type and end use), based on historical data and user-defined scenarios for future projections. In addition to supporting the interactive exploration of building stock dynamics, the model has been used to study the likely outcomes of specific policy and innovation scenarios targeting very low future energy consumption in the building stock. Model use has highlighted the scale of the challenge of meeting targets stated by various government and professional bodies, and the importance of considering both new construction and existing buildings.

Keywords: building stock, energy, efficiency, climate change, emissions, planning, new construction, renovation, retrofit

Introduction

Global emissions of greenhouse gases from fossil fuel combustion in 2004 were approximately 49 $GtCO_2eq$[1]. Of those emissions, 5.6 $GtCO_2eq$ were emitted in the United States. The commercial and residential building sectors were responsible for 18% and 21% of this total respectively (EPA 2008), or a combined 2.2 $GtCO_2eq$. That quantity is greater than the emissions from any country other than China and the US. In fact, the US commercial building sector alone was responsible for more emissions than any country in Europe. Given the scale of these numbers, it is almost inconceivable that any successful climate change mitigation scenario will fail to dramatically re-shape energy consumption in buildings. Fortunately, improving the energy efficiency of building stock is consistently projected to be one of the most effective and affordable ways to mitigate greenhouse gas emissions on a large scale. For example, the IPCC 4th Assessment report projects that cost effective energy efficiency measures in buildings would save 5.3-6.7 $GtCO_2eq$/yr globally by 2030 (IPCC 2007).

As advocates, analysts, and policy makers in the US explore greenhouse gas mitigation scenarios, they are increasingly articulating ambitious efficiency goals for US buildings.

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[1] Note that there are many different units in use for greenhouse gas emissions. 1 $GtCO_2eq$ is the equivalent warming potential of 1 Billion metric tonnes of CO_2. Some readers may be familiar with sources that use GtCeq, which only counts the weight of the carbon atoms emitted, and is thus equivalent to 12/44 of the corresponding $GtCO_2eq$ value.

One idea that is gaining popular support is “net-zero” annual energy consumption, combining more efficient building energy use with on-site renewable energy generation[2]. Specifically, there is a commitment to delivering net-zero energy new (and in some cases existing) commercial buildings by 2030 in the stated goals of the American Institute of Architects (AIA), American Society of Heating Refrigeration and Air conditioning Engineers (ASHRAE), the US Green Building Council (USGBC), the Illuminating Engineering Society of North America (IESNA), and Architecture 2030[3], and there are similar commitments by the US Department of Energy[4], in the law governing federal buildings[5], and by the California Public Utilities Commission in their Strategic Energy Efficiency Plan[6]. The statement of such goals is an important first step, but crafting appropriate R&D programs, deployment strategies and policies to meet these goals is a more difficult challenge than is often acknowledged. Meeting ambitious building efficiency targets will require a coordinated effort of building professionals, financiers, suppliers, contractors, building owners, building operators, building occupants, researchers and policy makers, and must address the diversity of energy saving opportunities found in different building types, mechanical systems, patterns of operation, climates and ownership structures, and throughout building lifecycles.

There is thus a growing demand for tools to support the analysis of energy use in the building stock over time. Such tools must address the heterogeneity of buildings and their energy end uses, and should be useful to users from a variety of backgrounds asking a variety of questions. The building stock modeling work outlined in this paper is an initial response to these needs. The same conceptual model has been implemented in three different computing environments (Excel, Analytica™[7] and Python[8]), and these have been exercised through a number of analysis and planning cases. The models have helped to clarify the practical meaning of mitigation goals, to identify scenarios that achieve stated goals, and to frame future analyses to evaluate the relative costs and benefits of these scenarios. The basic dynamics of the model have provided a number of key insights into building stock behaviour and the nature of the challenge of emissions reduction in buildings.

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[2] See Torcellini et al (2006) for a discussion of the several potential ways to define net-zero in terms of site or source energy, carbon emissions or cost.

[3] There is a joint MOU from this group at http://www.usgbc.org/News/PressReleaseDetails.aspx?ID=3124. The agreement is based on the 2030 Challenge calling for all new construction to be carbon-neutral by 2030. (Architecture 2030, 2007)

[4] Their Commercial Buildings Initiative targets net-zero commercial buildings by 2025 (CBI, 2007)

[5] Federal building performance standards in the Energy Independence and Security Act of 2007 Section 433 call for a 100% reduction in fossil fuel use in new construction by 2030 (FEMP Regulation, 2008)

[6] California’s long-term energy efficiency strategic plan calls for net-zero energy commercial buildings by 2030 (CPUC, 2007)

[7] Analytica™ is a visual mathematical modeling environment with built in support for sensitivity and uncertainty analyses

[8] Python is an open source interpreted programming language with many freely available mathematical and scientific programming libraries

Context and Motivations

A number of considerations were important in shaping the model structure and its implementations. Five key considerations and their consequences are described below.

1) **The ability to ask a variety of 'what if' questions:** For example, 'what would be the effects of ratcheting up the efficiency of new buildings over the next two decades, in the manner proposed by the AIA's 2030 Challenge?' or 'how much energy could be saved if new retail store HVAC and refrigeration technologies were introduced to the market in 2015?'. We have thus emphasized flexibility in the model structure and interfaces.
2) **Transparency and user interactivity:** While defaulting to sensible values, the model allows users to exercise their own judgment (or imagination) about many model inputs and parameters, such as stock turnover and retrofit rates, and on the uptake and impact of technologies, standards adjustments, etc.
3) **Support for uncertainty and sensitivity:** Uncertainty must be inherent in any such model projecting forward to 2030 or 2050. And since the model should assist in evaluating the relative importance of many considerations, it must be amenable to sensitivity analyses. As a practical matter, these features require support for representations of uncertainty in both inputs and outputs, many sequential runs with varying inputs, and appropriate analysis tools.
4) **Fast run times** were understood to be necessary to support both the uncertainty/sensitivity requirements and the ease of user interactivity. As a result, the model has a top-down structure that can scale from a single building category to a highly diverse and disaggregated set of thousands of categories and takes energy intensities as inputs (again scalable from a single category to a highly diverse set), rather than attempting to derive them bottom-up from first principles.
5) **Support for higher fidelity analyses** was a lower priority, but such work is still supported. The underlying data structures can be scaled to support arbitrarily detailed representations of energy end uses and construction, demolition and retrofit dynamics. And the model can be linked to external data sources (e.g. to more detailed real-estate projections) and to external applications (e.g. EnergyPlus for detailed modeling of individual buildings).

Beyond meeting the above criteria, this work has been motivated by the anticipation of three key applications.

1) **Helping to inform and flesh out the stated goals of building industry stakeholders and policy makers.** To date, most forward-looking goals set for the building sector have been aspirational. There has been limited analysis of their feasibility, their expected energy impacts, or identification and analysis of alternative approaches that might achieve the same reductions in energy consumption faster, with greater certainty, or at lower cost.
2) **Performing estimates of technical and economic potentials for the deployment of specific efficiency technologies**. These estimates could then be used to inform goal setting and to evaluate the impacts of policies and technologies as they are

implemented. At the same time, empirical data on the impacts of implementation programs could be used to refine model predictions.

3) **Performing optimizations of outcomes based on efforts constrained by time and resources.** Here “optimal” could be defined as the least expensive way to meet a given goal, the deepest energy/carbon savings, the greatest number of jobs created, the most robust, the fastest payback, etc.. The stock model would be used iteratively by optimization algorithms to identify optimal strategies.

Informed by the above considerations, the model structure we have produced can be characterized as adopting a top-down approach with relatively few inputs and fast run times. One logical complement to this approach would be a bottom-up model based on extensive building simulations designed to capture the effects of specific interventions when applied to individual buildings representative of the whole building stock. A project of this type has been carried out for the US commercial building stock by researchers at the National Renewable Energy Lab (Griffith 2007). It is hoped that these two approaches might meet successfully in the middle, but given our interest in supporting goal setting and high level policy design, there are important reasons for our initial focus on the top-down approach. Both individual buildings and the building industry as a whole have complicated interactions that shape the energy demands of the commercial sector. While there are ways to address these concerns using bottom-up models, they tend to require many small assumptions instead of a few big ones, and are thus less transparent, more subject to unintended structural bias in their design, and less accessible to policymakers and others who are trying to consider the possibilities. In recognition of these complications and the gross uncertainties involved in projecting ten to forty years into the future, we have been inclined to err on the side of simplicity and transparency.

Both the top down approach discussed herein and the building simulation approach of Griffith et al differ significantly from the techno-economic and macroeconomic approaches commonly used in other building stock energy models. Prominent examples of such approaches include the buildings module of the National Energy Modeling System (NEMS)[9], the World Energy Model used by the International Energy Agency to model reference scenarios for the World Energy Outlook (IEA 2008), the bottom up models supporting IPCC “economic mitigation potentials” (IPCC 2007), the buildings chapter of the US assessment known as “Scenarios for a Clean Energy Future” (Brown, Levine et al. 2001), the McKinsey “cost curve” analysis of abatement costs (Creyts 2007), and efficiency analysis and meta-analysis conducted by the American Council for an Energy Efficient Economy (Nadel 2004) and the Alliance to Save Energy in Energy in support of the Presidents Climate Action Plan (Loper, Capanna et al. 2008). Energy efficiency within bottom-up techno-economic models is understood as a property of equipment or appliances, expressed as service per unit of energy, with the end-use services (e.g. heating, cooling, lighting) usually considered as given inputs. The energy efficiency of a building is then considered as the weighted sum of the end-use efficiencies and the deployment of future end-use technologies is determined by the lowest discounted life-cycle costs. Macroeconomic models are based on statistical relationships

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[9] NEMS is a General Equilibrium Model (GEM) of macroeconomic processes that represent the US energy economy. NEMS is maintained by the US EIA (EIA 2003).

between economic conditions, energy use, and technology adoption derived from empirical data collected over time and their projections generally assume that such relationships will be preserved into the future. With either modeling approach, it can be difficult to account for the empirical lack of deployment of some measures with very low discounted life-cycle costs (such as energy-efficient lighting), the significant energy interactions between building subsystems, the passive provision of services (such as through passive solar design and insulation), or the avoidance or shifting of demands through occupant behaviour changes or re-imagining the nature of the service itself, for example providing occupant control of windows as a replacement for air conditioning. Very low energy buildings in particular tend to utilize well-integrated systems that are much more than the sum of their components and represent a significant departure from past performance. Therefore, neither techno-economic nor macroeconomic models can be expected to accurately model their widespread deployment. The approach described by this paper deals primarily with whole building energy consumption and allows efficiency adoption rates and gains of any magnitude to be supplied as inputs to specific scenarios. The assumptions and motivations behind specific scenarios must therefore be carefully scrutinized, a task which is facilitated by the relative simplicity of the model structure.

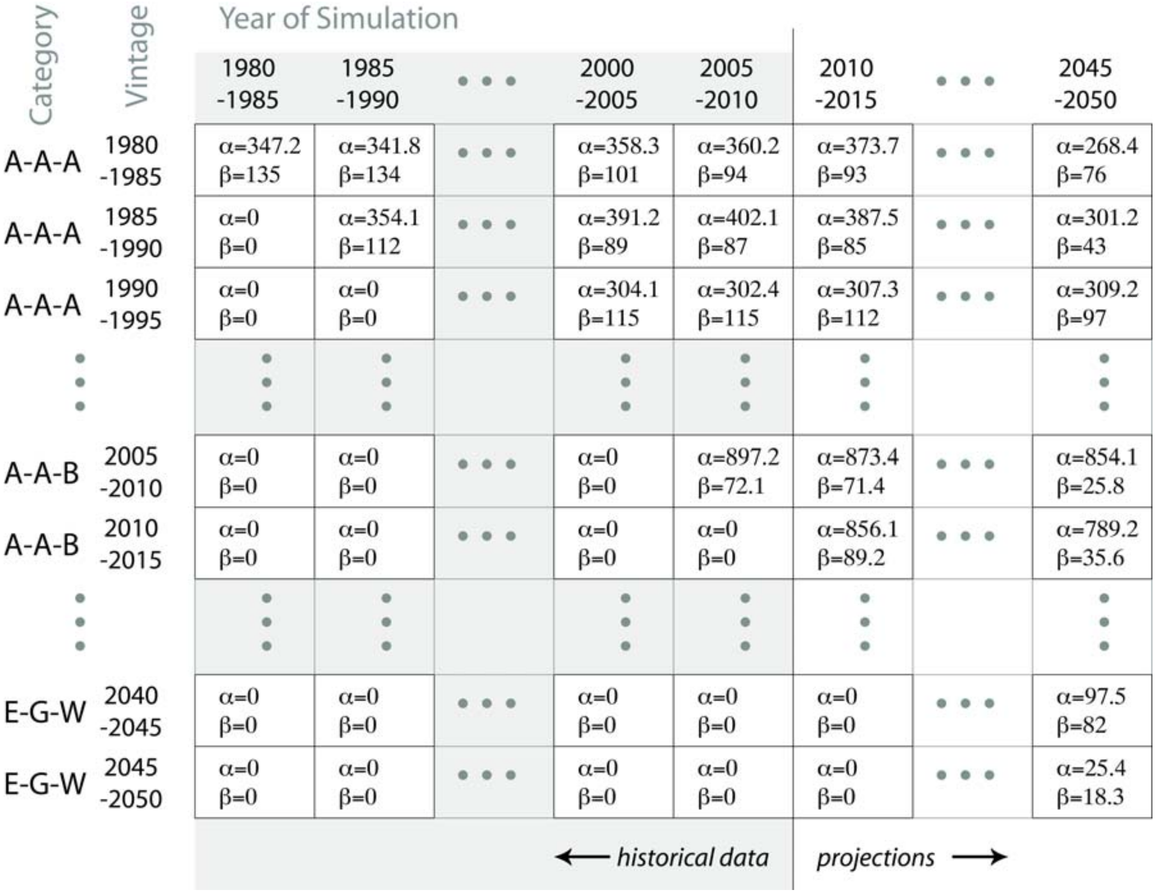
The last consideration to note is that of data availability. Because of the high degree of integration and customization in most low energy buildings, the best possible model of the US commercial building stock would contain an accurate representation of the full variety of such conditions for each individual building. However, the reality is that such a model would be far too complex to be of practical use and would require enormous amounts of data that are not currently available. Our approach has been to start with the cleanest, simplest, and most accessible data sources. Two key inputs include the US EIA Commercial Buildings Energy Consumption Survey (CBECS) at the national level, and California’s Commercial End Use Survey (CEUS) for similar data within California.

Model Description

Model structure

The overall approach is to discretize the stock into categories (e.g. by location, building type, size, vintage, building life cycle stage) and then to assign attributes (e.g. floor area, energy use intensity (EUI) by fuel type, maintenance cost) to each resulting category. The time-evolution of the stock is also considered in discrete steps (usually either one or five year steps), with the attributes in each category updated at each time step based on the model inputs. In Figure 1, the categories are described by the letters on the left, with each sub-category represented by a letter (e.g. A-A-A might be northern - offices - new, A-A-B might be northern - offices - recently renovated, and E-G-W might be western - schools - not yet retrofit or renovated). In this abstract diagram, the attributes of each category are represented as α (e.g. floor area) and β (e.g. EUI). This is the basic data structure at the heart of the model. To this is added initial stock data from one of our data sources (e.g. CBECS) and various user inputs that shape future attributes. Complete sets of inputs describe scenarios. The resulting historical data and projections are interpreted by a graphical interface that allows exploration of the results and provides various forms of aggregated data.

Figure 1: Essential model structure. In this example, α = floor area (millions of square feet), and β = energy use intensity (kBtu/ft^2)



Category	Vintage	Year of Simulation 1980 -1985	1985 -1990	• • •	2000 -2005	2005 -2010	2010 -2015	• • •	2045 -2050
A-A-A	1980 -1985	α=347.2 β=135	α=341.8 β=134	• • •	α=358.3 β=101	α=360.2 β=94	α=373.7 β=93	• • •	α=268.4 β=76
A-A-A	1985 -1990	α=0 β=0	α=354.1 β=112	• • •	α=391.2 β=89	α=402.1 β=87	α=387.5 β=85	• • •	α=301.2 β=43
A-A-A	1990 -1995	α=0 β=0	α=0 β=0	• • •	α=304.1 β=115	α=302.4 β=115	α=307.3 β=112	• • •	α=309.2 β=97
⋮		⋮	⋮		⋮	⋮	⋮		⋮
A-A-B	2005 -2010	α=0 β=0	α=0 β=0	• • •	α=0 β=0	α=897.2 β=72.1	α=873.4 β=71.4	• • •	α=854.1 β=25.8
A-A-B	2010 -2015	α=0 β=0	α=0 β=0	• • •	α=0 β=0	α=0 β=0	α=856.1 β=89.2	• • •	α=789.2 β=35.6
⋮		⋮	⋮		⋮	⋮	⋮		⋮
E-G-W	2040 -2045	α=0 β=0	α=0 β=0	• • •	α=0 β=0	α=0 β=0	α=0 β=0	• • •	α=97.5 β=82
E-G-W	2045 -2050	α=0 β=0	α=0 β=0	• • •	α=0 β=0	α=0 β=0	α=0 β=0	• • •	α=25.4 β=18.3

With this flexible basic structure, categories and attributes can be easily added or removed for model customization or further development. At its most detailed extreme, each building in the stock could be considered as its own category, and the attributes could be very detailed descriptions of each building. In practice, we have started with a few key categories and attributes, based partly on what is most important and partly on what data is currently most readily available.

Categories, Attributes and Historical Data

For the implementations discussed below, the stock is categorized by region, building type, vintage and life-cycle stage, and the attributes are floor area, EUI broken down by fuel type and end use, and CO_2 emissions. For the national model, based on CBECS data, these categories are as shown in Table 1.

Table 1: Categories for national CBECS-based model

Region	*Building Type*	*Vintage*	*Life-Cycle Stage*
Northern Western Southern Mideastern Eastern (census regions)	Large Office Small Office Large Retail Small Retail Hotel Restaurant Hospital School Supermarket Warehouse Other	pre-1990 1990-1995 1995-2000 2000-2005 2005-2010 2010-2015 2015-2020 2020-2025 2025-2030	Untouched Renovated Retrofit

In this national model, the attributes for each of the categories with vintages less than 2010[10] are filled in with historical data from CBECS. For the California model, similar categories are used, and the pre-2010 data is filled in with historical data from CEUS.

For the pre-2010 vintages, all of the floor areas are placed in the Untouched category, and may move from there into the Renovated or Retrofit categories in future years, depending on the user inputs. We included these two renovation/retrofit categories to allow for a distinction between buildings being renovated for architectural or functional purposes (and thus providing opportunities for efficiency improvements at the same time, possibly very significant) and those retrofit explicitly for energy efficiency (presumably with some payback period requirement). From a practical perspective within the model, they allow the user to define two different levels of energy savings for actions on the existing stock. Additionally, there is a ‘tune-up’ variable that allows for smaller changes in the Untouched category. This represents the kinds of low-cost, no-cost “adjustments” made to building operations through retrocommissioning and related programs that have been shown to save 5-10% of energy consumption at very low cost. (The ‘tune-up’ percentages noted below are average savings for all buildings in the Untouched category.) Further levels of retrofit may also be considered within the model structure, and may be of interest in further model development.

CBECS data

The Commercial Buildings Energy Consumption Survey is a “national sample survey that collects information on the stock of U.S. commercial buildings, their energy-related building characteristics, and their energy consumption and expenditures.” This survey is conducted once every 4 years, with the results from 2003 serving as the most recently published data. For each CBECS, buildings from a statistical random sample (5215 buildings in 2003) are administered detailed surveys about their physical characteristics, equipment, operation, and energy consumption. The results from these surveys are weighted according to the number of buildings in the total stock that each surveyed

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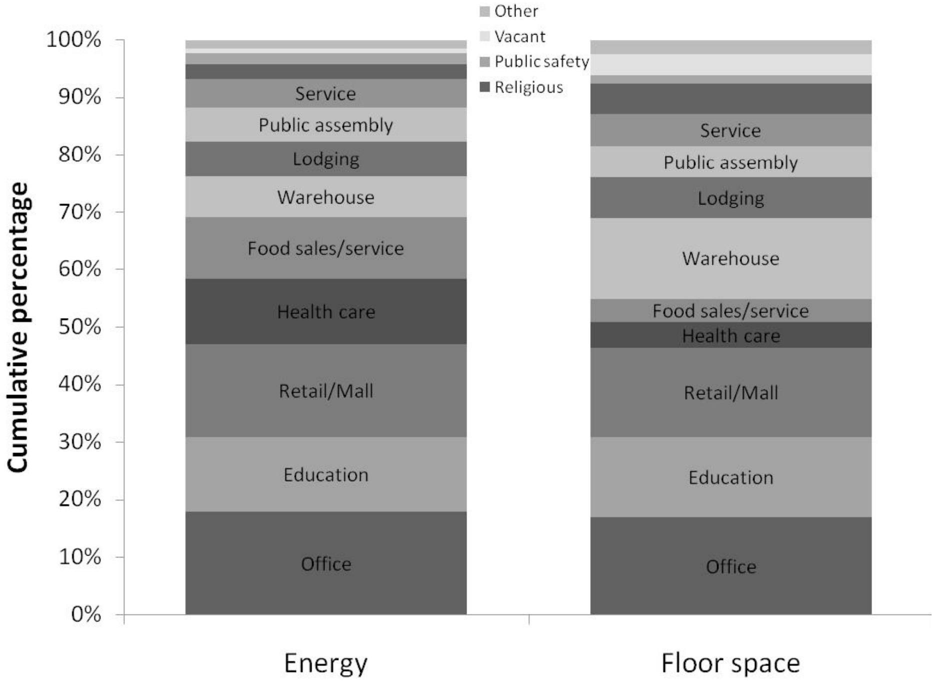
[10] Technically, vintages less than 2003 are filled in with the available historical data, and then vintages to 2010 are projected forward based on 2003 data and stock growth trends – these years are not considered for user inputs since these buildings are generally already either part of the stock or beyond the design phase.

building is expected to represent and the results are normalized to aggregate energy consumption data. Figure 2 illustrates the percentage of total energy consumption and floor space each primary CBECS building type contributed in the most recent published data. The floor space, weight factors, EUI values, and stock categories found in the CBECS survey results are ideally suited for use as inputs into the stock model.

Figure 2: US commercial building stock energy consumption and floor space as described by CBECS. Source: CBECS 2003



User Inputs and Interactions

As one may imagine, the model structure allows for the creation of a wide variety of user interfaces and input controls. We believe that a simple collection of user inputs are of the greatest utility for national-level hypothetical stock model calculations. These user inputs are as shown in Table 2, along with several of the basic default values for the stock growth inputs (based on projections made by the EIA in their 2008 Annual Energy Outlook; note that as of the publication date of the paper and likely over the next few years the default new construction numbers are far higher than actual construction starts, reinforcing the need for, and value of, the uncertainty features described later). These inputs include the rates of new construction, retrofits and demolition and the expected energy improvements associated with new construction, retrofit and tune-ups over time.

Table 2: Essential user inputs in simplest standard interface.

Stock Growth annual % rates of change	
new	2.3%
renovated	2.3%
retrofit	-
retired	0.8%

EUI - % Better than 2005				
	2010-2015	2015-2020	2020-2025	2025-2030
new	-	-	-	-
renovated	-	-	-	-
retrofit	-	-	-	-
tune-up	-			

These inputs may be applied at the global level (i.e. all building types, nationally), or they may be applied to the different building stock categories individually. Even more detail is possible through associating EUI improvements with individual energy end uses. Users interested in even more detailed control can use the model backend to manipulate the data directly or provide other algorithms to change the projected data as desired. By default, the outputs are graphs of floor area changes, total energy consumption, and CO_2 emissions and EUI by fuel type.

Calculations

The model works with two primary attributes for each category: floor area and EUI. Other attributes either feed into these two (e.g. EUI by fuel type and end use), or are related to them (e.g. CO_2 emissions per square foot). The floor area calculations use the ‘Stock Growth’ inputs from Table 2, and the EUI calculations use the ‘EUI’ inputs. The product of the floor area and EUI is the energy consumption.

Floor Area

The floor area for each (post-2010) category is calculated with the user-supplied growth rates (new construction [c], renovation [r], retrofit [f] and retirement / demolition [d]), where new construction adds floor area to the Untouched category, renovation or retrofit moves floor area between life-cycle categories, and demolition removes floor space. In the following equations, t represents the year of the simulation, the index i represents a particular region and building type, j represents a particular vintage, and the floor area in the Unchanged, Renovated and Retrofit categories are noted as U_A, R_A and F_A respectively.

$$A[t]_{U,i,j} = \begin{cases} 0 & \text{if } t < j \\ c_i \cdot \sum_k \left(A[t-1]_{U,i,k} + A[t-1]_{R,i,k} + A[t-1]_{F,i,k}\right) & \text{if } t = j \\ (1-d_i) \cdot A[t-1]_{U,i,j} & \text{if } t > j \end{cases}$$

$$A[t]_{R,i,j} = r_i \cdot A[t-1]_{U,i,j} + (1-d_i) \cdot A[t-1]_{R,i,j}$$
$$A[t]_{F,i,j} = f_i \cdot A[t-1]_{U,i,j} + (1-d_i) \cdot A[t-1]_{F,i,j}$$

EUI

Leaving aside the slight complications introduced by the tune-up factor, the energy use intensity for a given category is calculated quite simply, given the user input of percentages better than 2005 values (denoted by the variable e in the equations). This calculation can also be done for each end use independently, if the user provides separate input values.

$$
\begin{aligned}
EUI_{U,i,j} &= (1 - e_{c,i,j}) \cdot EUI_{U,i,2005} \\
EUI_{R,i,j} &= (1 - e_{r,i,j}) \cdot EUI_{U,i,2005} \\
EUI_{F,i,j} &= (1 - e_{f,i,j}) \cdot EUI_{U,i,2005}
\end{aligned}
$$

Energy

The energy consumption of a given building stock category at time t is determined by multiplying the floor space in that category by the EUI associated with that category.

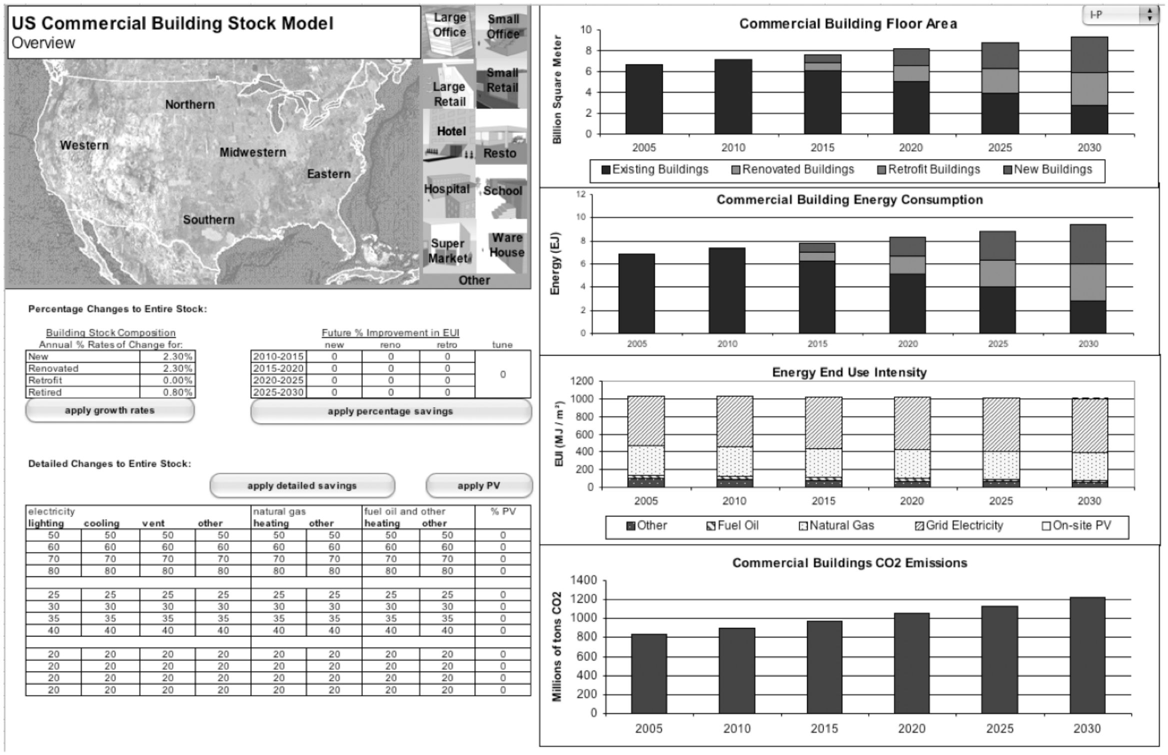
$$
\mathrm{Energy}[t]_{X,i,j} = A[t]_{U,i,j} \cdot EUI_{U,i,j}
$$

Given the final set of stock data indexed over all the years of the simulation, it is also possible to calculate for any given year the energy contributions from specific building types, locations, and vintages, life-cycle stage and for each energy end use. With known emissions factors for the specific fuel types used to meet end uses (these can be regionally disaggregated), it is possible to calculate the CO_2 emissions associated with various scenarios. Finally, with the costs associated with the fuels used to provide buildings energy and the upfront and maintenance costs of stock interventions, it is possible to calculate the net cost of specific scenarios over time. These features of the stock model present many opportunities for future creative exploration and optimization.

Model Implementations

To date, we have implemented versions of the building stock model on three different platforms: Excel with Visual Basic for general use; Analytica™, a more sophisticated modeling platform for explicit treatment of sensitivities and uncertainties, which we feel is a critical feature for any planning model with a time horizon of 20-50 years; and most recently in the programming language Python for increased flexibility and complexity in defining building stock and scenarios. The main screen of the interface for the Excel version is shown in Figure 3. This version is intended to be easy to use for a general audience, and is the simplest version. The Analytica™ and Python versions have more capabilities, but somewhat less developed interfaces, and have been used primarily for in-house modeling.

Figure 3: Screenshot of Excel-based model



Percentage Changes to Entire Stock:

Building Stock Composition
Annual % Rates of Change for:

New	2.30%
Renovated	2.30%
Retrofit	0.00%
Retired	0.80%

Future % Improvement in EUI

	new	reno	retro	tune
2010-2015	0	0	0	0
2015-2020	0	0	0	
2020-2025	0	0	0	
2025-2030	0	0	0	

Detailed Changes to Entire Stock:

electricity				natural gas		fuel oil and other		% PV
lighting	**cooling**	**vent**	**other**	**heating**	**other**	**heating**	**other**	
50	50	50	50	50	50	50	50	0
60	60	60	60	60	60	60	60	0
70	70	70	70	70	70	70	70	0
80	80	80	80	80	80	80	80	0
25	25	25	25	25	25	25	25	0
30	30	30	30	30	30	30	30	0
35	35	35	35	35	35	35	35	0
40	40	40	40	40	40	40	40	0
20	20	20	20	20	20	20	20	0
20	20	20	20	20	20	20	20	0
20	20	20	20	20	20	20	20	0
20	20	20	20	20	20	20	20	0

To run a scenario in the Excel implementation, the user inputs the stock growth rates and percentage savings numbers (the input tables directly below the map in Figure 3 correspond with the inputs shown in Table 2, while the larger input tables on the bottom left of Figure 3 allow for more detailed inputs about particular end-use savings and on-site PV), and then hits the apply button(s) corresponding to any changes made. The calculations are then carried out as described above. The resulting graphs of floor area, stock energy consumption, EUI and CO_2 emissions are then displayed on the right side of Figure 3. The map in the top left corner of Figure 3 is interactive, allowing the user to zoom in and out of different region and building-type categorizations, to provide either global or category-specific inputs and to view the results at various levels of granularity.

Scenario and Target Analyses

Analysis of 2030 Challenge and Related Net Zero Energy Goals

The 2030 Challenge, put forth by Ed Mazria and the AIA, is for building designers to start delivering buildings that are 50% more efficient than existing stock right away, and then follow a schedule of progressively more efficient buildings over the next two decades – starting at 60% below average existing energy use by 2010, then 10% more efficient every 5 years until all new buildings are net-zero energy consumers by 2030. Although achieving even these goals is a very significant technical and policy challenge, our analysis has shown that if all new buildings followed this trajectory but the efficiency of the existing stock did not change, then the total stock energy consumption would decrease only slightly between 2010 and 2030. Naturally, the tools and techniques used to deliver increasingly efficient new buildings would influence what can be achieved with retrofits of existing spaces. The 2030 challenge also includes a 50% improvement for all renovated buildings starting in 2010 (and remaining at 50% thereafter[11]), with the renovation rate (in terms of floor area) assumed to be equal to the new construction rate. With this consideration, the impacts are much greater, but still only bring the stock energy consumption down to 1990 levels by 2030. Figure 4 shows this scenario, along with a business as usual (BAU) scenario and another scenario that we felt was perhaps as aggressive as one might reasonably consider (derived from planning work with Canadian and Mexican government groups (Commission, 2008)), the inputs for which are shown in Table 3.

Figure 4: Three scenarios for building stock improvements

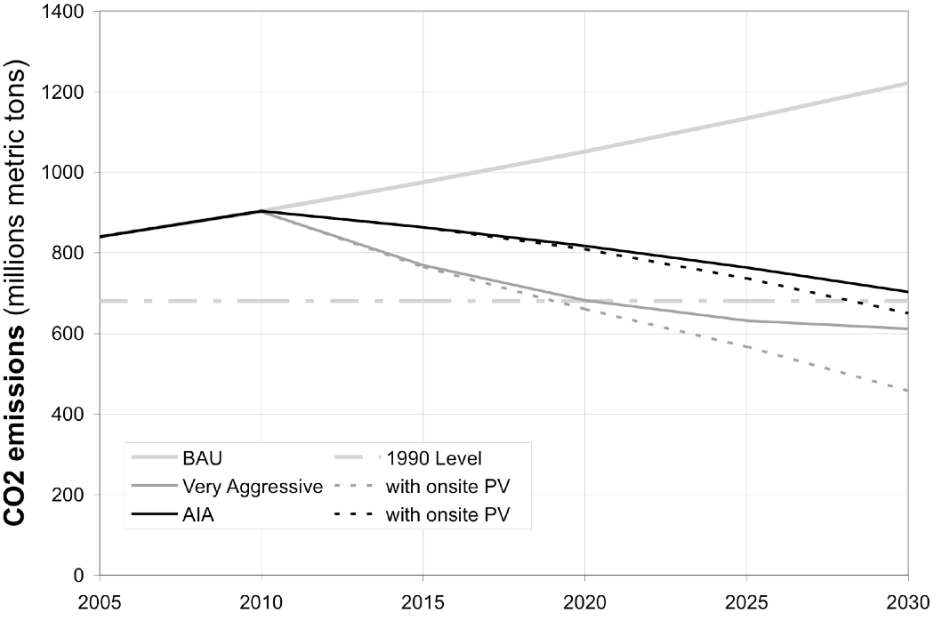


Table 3: The inputs used to create the "Very Aggressive" scenario shown in Figure 4. In parentheses are the percentages of post-efficiency electricity demand met by onsite PV.

Stock Growth annual % rates of change	
new	2.3%
renovated	2.3%
retrofit	0.95%
retired	0.8%

	Future % Improvement in EUI			
	2010-2015	2015-2020	2020-2025	2025-2030
new	55% (5%)	57.5% (20%)	60% (50%)	62.5% (100%)
renovated	47.5% (3%)	49.2% (15%)	50.9% (40%)	52.5% (80%)
retrofit	20% (2%)	28.3% (10%)	36.7% (20%)	45% (50%)
tune-up	2.8%			

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[11] An earlier version of the Challenge had this staying constant at 50%, but a newer version has this ramping down in the same way as with new construction. We did the original analyses with the earlier version (which seems somewhat more in line with what practitioners currently feel is plausible), and have kept the graphs as such herein.

For purposes of this analysis we assume the carbon intensity of existing central plants and fuel supplies remains constant. In fact regulatory action in some states and carbon taxes or cap and trade should reduce the carbon intensity of electricity from central plants over time but in the 20 year time frame considered here these effects are not likely to be large, thus we focus more on energy use reductions in buildings.

These results highlight the scale of the challenge to reduce energy use and emissions. Just to reach 1990 emissions levels by 2030 will require larger decreases in energy consumption for all new construction and retrofits than have historically been observed in all but a tiny subset of the market. The results also highlight the importance of floor area growth and turnover rates in any such scenario analysis, and they demonstrate the key importance of improving existing building energy performance if any substantial savings are to materialize within the 2030 timeframe.

California AB32 Studies

With the passage of Assembly Bill 32, California committed to returning its greenhouse gas emissions to 1990 levels by 2020 and set a goal of reducing emissions to 80% below 1990 levels by 2050. The stock model was used to examine the potential for the building sector to contribute its share of the AB32 goals and to highlight some potential pathways capable of reaching them. Variants of the Excel and Analytica™ models were used for these studies, which we ran using two models: one based on CEUS data (rather than the national CBECS), and the other simplified to have just one building type and location (and just one retrofit/renovation category) and with normalized EUI values. Figure 5 shows four scenarios of energy consumption produced during this analysis that compare the contribution from untouched, retrofit, and new buildings.

Figure 5: Four scenarios of building stock energy consumption compared to California's AB32 goals.

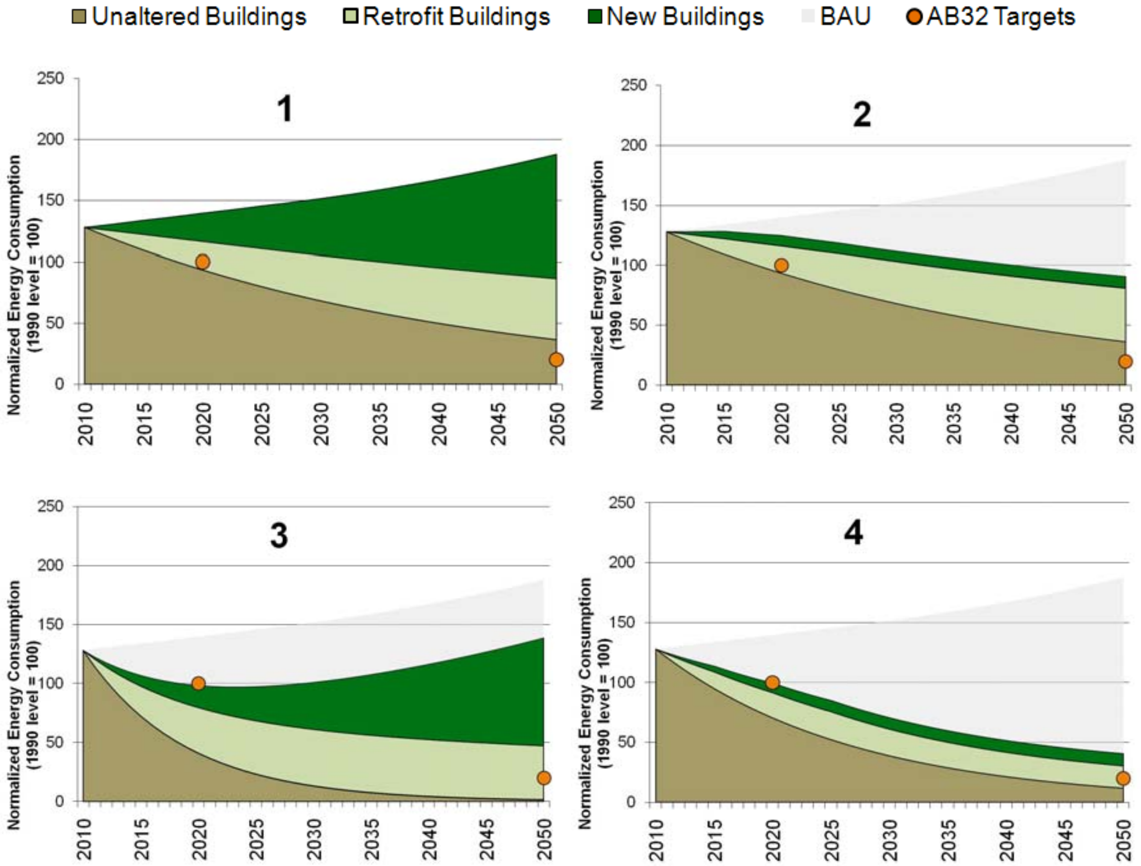


Table 4: Inputs used to generate the scenarios in Figure 5

Scenario	% change	EUI Improvements
1: Business as Usual	new=2.3% renovated=2.3% retired=0.8%	Ramping up to 20% improvement in new buildings and 12.5% in existing efficiency by 2025
2: Max new construction	new=2.3% renovated=2.3% retired=0.8%	Ramping up to net-zero energy new buildings by 2020 and a 25% improvement through retrofits by 2025
3: Max retrofit	new=2.3% renovated=10.0% retired=0.8%	50% improvement through retrofits, starting in 2010, new buildings hold steady with 25% improvement
4: Close to targets	new=2.3% renovated=5.0% retired=0.8%	New construction ramps from 70% to 99% between 2010 and 2030 and retrofits ramp from 50% to 80% over the same period

Scenario 1 is business as usual (BAU). It projects modest improvements in building efficiency and continues an upward trend. Scenario 2 is based on extremely aggressive improvements in new construction. 100% of new buildings after 2020 are net-zero energy, but note that this scenario does not come close to the 2050 climate target. Scenario 3 shows deep cuts from retrofits that are eventually overwhelmed by the energy use of new construction. Scenario 4 attempts to reach both AB32 targets, but requires some very aggressive assumptions. These results again highlight the importance of retrofitting the existing stock, but also show the growing importance of new construction when looking out to the 2050 planning horizon. These results underscore the enormous magnitude of the challenge of lowering the energy consumption of our building stock to the targeted levels.

An analysis of the effect of uncertainties (using the Analytica™ model) in the rates of new construction, retrofits, and demolition on energy demand for scenario 4 is shown in Figure 6. Note that there is substantial variation in the potential outcomes, with the 5th and 95th percentiles representing a range of 45-70% below 1990 levels. Table 4 provides more details on the inputs used to describe the scenario and its uncertainties.

Figure 6: Data from Analytica™ implementation of stock model showing the 5th, 25th, 50th, 75th, and 95th percentile of results for scenario 4 above.

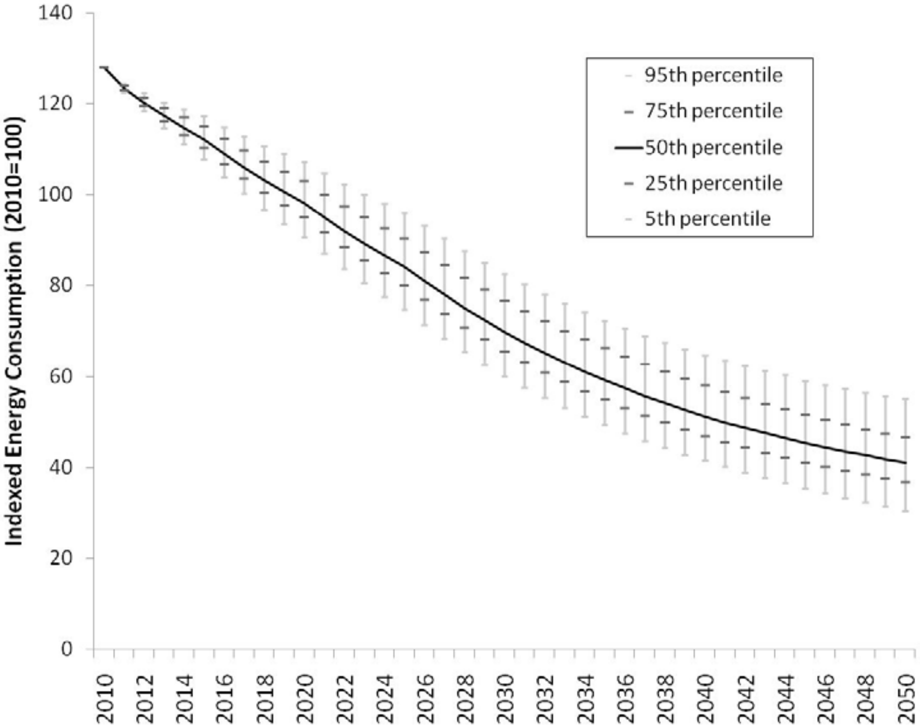


Table 4: The inputs used to create the uncertainty scenario shown in Figure 6.

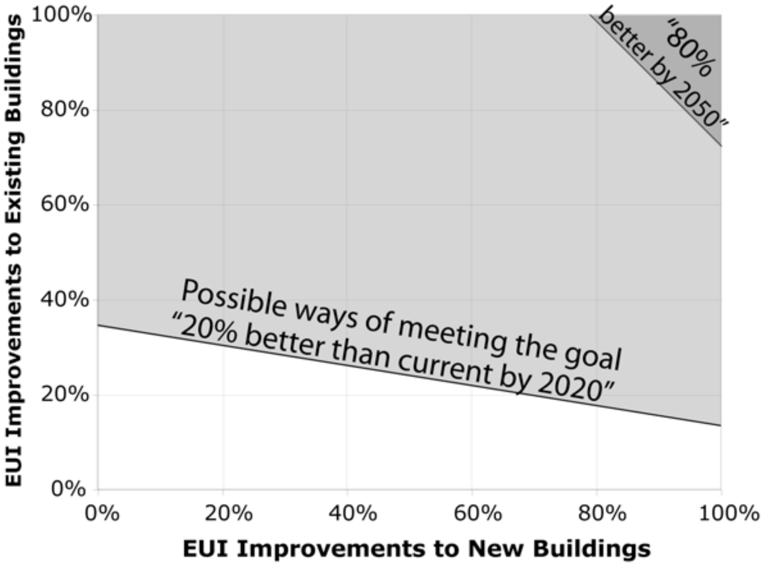
Stock Growth annual % change, with uncertainty	
new	Triangular distribution 0%, 2.3%, 3%
retrofit	Normal distribution Mean 5.0%, SD 0.5%
retired	Normal distribution Mean 0.8%, SD 0.3%

Future % Improvement in EUI				
	2010-2015	2015-2020	2020-2025	2025-2030
new	70%	80%	90%	99%
retrofit	50%	60%	70%	80%
tune	1.0%			

Options for Hitting Specific Targets

In cases where targets are pre-defined, the model can be used iteratively to find scenarios that can meet those targets, as discussed for the California AB32 goals above. Some amount of trial and error is useful, since it can help the user to better understand the relative importance of different factors. However, the tool can be used in a more systematic manner to consider the variety of ways that the targets might be met. Figure 7 shows a simple example that looks at the various ways of meeting the AB32 goals, given the default stock growth rates. The only variables considered are the percentage savings in new construction and the percentage savings in the existing stock. Attainment of climate targets is mathematically impossible if certain combinations of these two values are not achieved. Note how limited the options are for meeting the "80% better by 2050" goal.

Figure 7: Target meeting possibilities for the AB32 goals



Discussion

Implications of Case Study Results in Policy and Research Context

In each of the cases studied, the importance of energy retrofits in existing buildings loomed large. It also became clear that the magnitude of the savings rates needed to achieve the climate mitigation goals are very challenging and that the applicable mix of new and existing building strategies varies depending on the savings target and time allowed to reach the target.

2020 vs. 2050

Given the long life of buildings, we can expect large portions of the total building stock today to still be in service in 2020 and many well past 2050. Hitting 2020 targets will be mostly a matter of updating existing buildings (or vastly changing their turnover rate). At timescales out to 2050, however, updates are not enough, and achieving aggressive energy savings goals becomes more dependent on innovation in new buildings.

Retrofits and Renovation

Retrofits, as measured by affected square footage and delivered performance, have a leading role to play in efforts to dramatically reduce greenhouse gas emissions associated with buildings. Since retrofit technologies, policies and costs are often different from those associated with new buildings, they will require their own focused research efforts and implementation pathways.

Model Validation and Calibration

Since key model attributes can be input by the user, it is natural to wonder how scenarios should be validated. There are two recommended approaches for doing so. The first is to validate the assumptions and logic behind the inputs. The second is to compare the outputs to common sense performance, past trends, and the outputs of other modeling approaches. In the case of the scenarios modeled in this paper, initial floor areas and energy intensity values were taken directly from standard government sources and initial levels of energy consumption therefore matched published government values. The rates of new construction, demolition, and retrofit used as inputs were taken to be similar to historic trends derived from published data by default. For the business as usual scenarios, percentages of efficiency improvement were taken to be just slightly higher than past percentages. For cases where the inputs are based on existing proposals (e.g. the Architecture 2030 Challenge), the explanation and justification of assumptions is left to the organizations behind the proposals. For scenarios designed to evaluate the feasibility of achieving specific targets, the inputs, such as accelerated rates of energy retrofits in existing buildings, and improved percentages of energy savings are presented to the reader for evaluation. Finally, the energy projections of the Business as Usual scenario are slightly lower than the official Energy Information Agency projections, but given the slightly more aggressive assumptions, this is to be expected.

Strengths and Limitations of the Model Structure

The tool usage to date underscores the potential value of building stock models to policy makers and researchers as they develop broad scenarios and planning options and evaluate them against their own performance criteria. And it has confirmed that a simple top down model can provide valuable insights into the dynamics of energy use in buildings over time and can support planning and analysis of climate mitigation targets and implementation pathways. As noted previously, this top-down approach facilitates transparency of assumptions, macro-level sensitivity analysis and user-interactivity. But there are, of course, down-sides to this simple top-down approach. The model does not explicitly consider the details of such things as the mechanisms of technology adoption or interactions between sectors of the economy and so is limited in how much insight it can provide about particular drivers and barriers to change. And with such a high-level model, the validity of the results are heavily dependant on user expertise in determining appropriate values for high-level inputs.

As noted in the Future Directions section, the model structure's flexibility and expandability does allow for the development of more detailed models requiring more lower-level inputs (hopefully finding the most appropriate trade-off points between the benefits of simplicity / transparency and depth / detail for the questions at hand). However, the model structure does have some inherent limitations and challenges in attempting to capture some important stock-evolution phenomena. One such challenge is the consideration of EUI spreads within particular categories. There is a wide range of EUI values in the stock, and the average value for any given category may not be as important for retrofit or new construction analysis as is the spread within that category (particularly in cases where one may wish to identify the lowest-hanging fruit). This may require an expansion of the attributes in each category to consider a mean EUI and a standard deviation (for which the Analytica™ model is well suited), and will require more consideration of how best to analyze and present the resulting outputs. A more important concern, and possibly a more strict limitation of the model structure, is in dealing with the details of existing buildings. These buildings are not static, and leveraging their existing processes of change will be important in improving the efficiency of the stock. As such, one may wish to explicitly model the routine turnover of particular equipment as well as policies and strategies designed to accelerate investment in more efficient building systems. This modeling of equipment turnover does not fit nicely into the current model structure, without an ugly explosion of the number of categories, or without simply accounting for this turnover in an external model and feeding the results into our model. Devising a similarly simple and powerful stock model that can explicitly account for equipment turnover in existing buildings remains an open challenge.

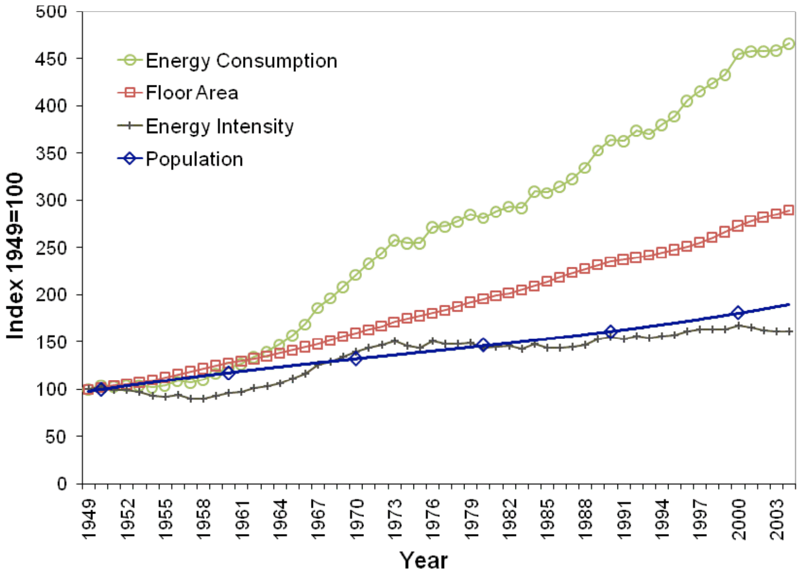
Future Directions

The general structure of the stock model described here is flexible enough for to include more detailed stock categories and to link to more detailed sources of economic data and projections (e.g. building starts projections in various regions) and energy use data. The quality and quantity of measured building energy data in the US are both increasing, so this model flexibility may prove very useful in further development and use. However, without policy intervention, several lines of inquiry may remain out of reach due to insufficient building stock data. In California there is movement towards mandatory energy use disclosures (similar to existing EU standards) at the time of sale or lease of commercial properties. If such data becomes publicly available, then it will support much higher fidelity versions of the building stock model and reveal important clues about how efficiency measures are working in practice. On the other hand, our findings from initial tool use suggest that many of the key policy and planning questions currently being asked operate at the whole stock level, suggesting that there could be more gained from a continued focus at this level in further model development before delving into the expansion of categories and attributes. To the extent that aggressive reductions in building energy use becomes more of a national priority both approaches should be pursued in parallel.

The model is currently structured to take exogenous inputs for EUI (or disaggregated end-use EUI) values for each category. With the model implementations used in the initial studies, these values for future years were derived based on 2005 EUI values in each category, along with user-input ‘better than 2005’ percentage savings. But we may also be interested in exploring the impacts of particular changes to some of the very wide variety of physical and occupant-behaviour factors that impact building energy use. With the current configuration, the user could model this by calculating the energy savings externally and then inputting these values into the model. However, the model could be extended such that the attributes in each category include information necessary to describe a building energy model, and with the end-use EUI values then treated as functions of an embedded building model. Such a configuration has been tested with the Excel version of the model, linked to EnergyPlus models of template buildings for particular stock categories. This could be further extended and tested in future research. It would allow users to input changes in physical building attributes and occupant behaviours over time, and have the model calculate the resulting changes in EUI in each category and then aggregate the results for display as is currently done. It would thus facilitate ‘what if’ questions about particular technologies or behavioural changes. And in combination with cost estimates for such changes and within a parametric search or optimization framework, it could be used to analyze and/or identify potential implementation pathways in much greater detail.

Energy use can be idealized as the product of total building floor space and EUI, but both parameters are likely to be dependent on population size. Figure 8 illustrates the time evolution of total energy, EUI, population, and floor space between 1949 and 2003, all scaled to arbitrary common units such that each is equal to 100 units in 1949, and percentage changes in each are therefore easily legible over time. The growth in floor space has outpaced both EUI and population. As such, potential strategies for reducing total stock energy consumption could involve better utilization of existing floor space and slowing overall floor space growth. (The recession of 2008-2009 will provide interesting new data on how dramatically our assumptions about continuous growth in floor space can be quickly reshaped by other business and economic investment trends.) These floor space options could not be easily tracked using EUI metrics. So future versions of the model should optionally display results in per-capita terms, per unit Gross Domestic Product, or other parameters as well as the traditional per-floor space. And different commercial sectors might have their own unique metrics- e.g. hotels might use per guest night.

Figure 8: Drivers of energy consumption in the US commercial building stock. Sources: CBECS, PNNL, Census, and EIA



We cannot expect buildings to become 100% efficient, i.e. require no energy for effective annual operations. The most generous estimates of savings potential are generally in the 60-80% range based on current energy end use. Renewable resources, on site or remote, are then required to convert these very low energy buildings to a net zero energy stock. The balance between investment in efficiency and renewables is the subject of ongoing discussion and is a function of building type and size, location, financing options, and cost/performance ratio of renewable sources. The stock model could be useful in this analysis. In particular, it could be used in considering stock-level impacts – as the total building stock becomes more efficient, existing large scale renewables (e.g. hydro) could form a larger percentage of the power mix, thus reducing carbon intensity.

Other useful applications of this model structure could be in custom implementations for particular states, cities, companies or government organizations interested in scenarios for their own set of buildings. In such cases, it could be of interest to combine this modeling structure (possibly with each building in the portfolio being its own category) with existing tools for benchmarking and portfolio-level retrofit analyses.

One particularly urgent set of issues relating to the US building stock is the planning and execution of the portions of stimulus spending for the American Recovery and Reinvestment Act tied to building weatherization, retrofits, and overall energy improvements. As it currently stands, the building stock model is theoretically well positioned to address questions of cost, jobs, energy savings and emissions reductions associated with these plans, but specific inputs, or at least estimates on the expected project costs, outcomes, and labor requirements would need to be gathered.

Conclusions

The building stock model of energy use and carbon emissions has been shown useful in planning. It has highlighted the importance of particular variables, particularly those relating to the existing stock – garnering significant improvements in existing buildings will be essential to meeting any goals on the 2020 or 2030 timescale and even on the 2050 timescale. And it has highlighted the magnitude of the challenge of meeting a range of publicly stated national and state policy goals. Even just returning to 1990 emissions levels will require significant and historically unprecedented decreases in energy consumption for all new construction and retrofits. Climate-related energy and carbon reduction goals are likely unattainable for the building sector without significant policy intervention focused on large scale deployment of efficient technologies and operational strategies in both new and existing buildings coupled with R&D programs that deliver ever increasing efficiency gains at lower cost and risk.

We intend to further develop the stock model over time to aid in continued policy and R&D planning. It has already played an important role in early planning activities, and we expect that it will become an even more critical tool as we move from statements of grand goals to pathways of implementation.

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DISCLAIMER

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