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# A Buildings Module for the Stochastic Energy Deployment System

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**ABSTRACT**

The U.S. Department of Energy (USDOE) is building a new long-range (to 2050) forecasting model for use in budgetary and management applications called the Stochastic Energy Deployment System (SEDS), which explicitly incorporates uncertainty through its development within the Analytica® platform of Lumina Decision Systems. SEDS is designed to be a fast running (a few minutes), user-friendly model that analysts can readily run and modify in its entirety through a visual programming interface. Lawrence Berkeley National Laboratory is responsible for implementing the SEDS Buildings Module. The initial *Lite* version of the module is complete and integrated with a shared code library for modeling demand-side technology choice developed by the National Renewable Energy Laboratory (NREL) and Lumina. The module covers both commercial and residential buildings at the U.S. national level using an econometric forecast of floorspace requirement and a model of building stock turnover as the basis for forecasting overall demand for building services. Although the module is fundamentally an engineering-economic model with technology adoption decisions based on cost and energy performance characteristics of competing technologies, it differs from standard energy forecasting models by including considerations of passive building systems, interactions between technologies (such as internal heat gains), and on-site power generation.

## Introduction

The perception that our energy future looks increasingly uncertain, and that climate change requires us to explore radically different technology pathways has precipitated the search for new or accelerated technology research and development (R&D) and the analysis tools necessary to guide it. The work presented in this paper is part of the ongoing development of the Stochastic Energy Deployment System (SEDS), which follows in a long history of modeling in support of planning and budgetary activities at the U.S. Department of Energy (USDOE). SEDS

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was commissioned to better support management, research direction, and budgetary decision-making for future R&D efforts. Specifically, it will be used to comply with the Government Performance Results Act of 1993 (GPRA), which requires federal government agencies, including USDOE, to predict and track the results of their programs and report them as a part of their obligations to the U.S. Congress (Gumerman 2005). While this process may at first blush seem like a harmless bureaucratic exercise, the wider implications of research budgets and priorities being determined based on faulty or misleading forecasts are serious. At a minimum, misdirection of limited public R&D funds could result. By developing SEDS, USDOE seeks to develop a tool that will help define a range of possible outcomes rather than accepting a potentially misleading scalar prediction, and to aid in the development of programs robust to our uncertain destiny.

SEDS is not intended to be a replacement for the Energy Information Administration's (EIA's) National Energy Modeling System (NEMS), which provides the basis for the Annual Energy Outlook (AEO), and subsequently for many energy policy studies. Rather, SEDS is an adjunct that allows modeling of economy-wide energy costs and consumption out to 2050 (NEMS currently forecasts to 2030) with minimal user effort or expertise. SEDS emphasizes characterizing the robustness of expected benefit streams of new technologies given the uncertain nature of energy futures, whereas NEMS is solidly rooted in historic and current conditions. To achieve fast execution, SEDS must run with variable time steps of, at a minimum, 0.5, 1, or 2 years. Also in the interests of speed and because the belief that global equilibriums are rarely experience in the real-world, no iterations towards solutions in one time step are allowed; rather outputs from one time step are inputs to the next.

This paper briefly describes the motivation for SEDS, but it is primarily focused on the effort to develop the first incarnation of the building sector module, the *SEDS Lite Building Module* (SLBM). This effort creates a rare opportunity to address some of the fundamental concerns that are widespread in the building energy simulation and forecasting community, such as: representing building end-use interactions, allowing competition between active and passive approaches, recognizing the key role of retrofits of existing buildings, integrating selection of on-site generation, etc. The entire SEDS project is evolving, and the motivations for reporting on the approach at this time to this audience include the hope that feedback from the building energy modeling community can guide the future shape of SLBM. Note that the future direction of Federal buildings energy research will rest in part upon its results.

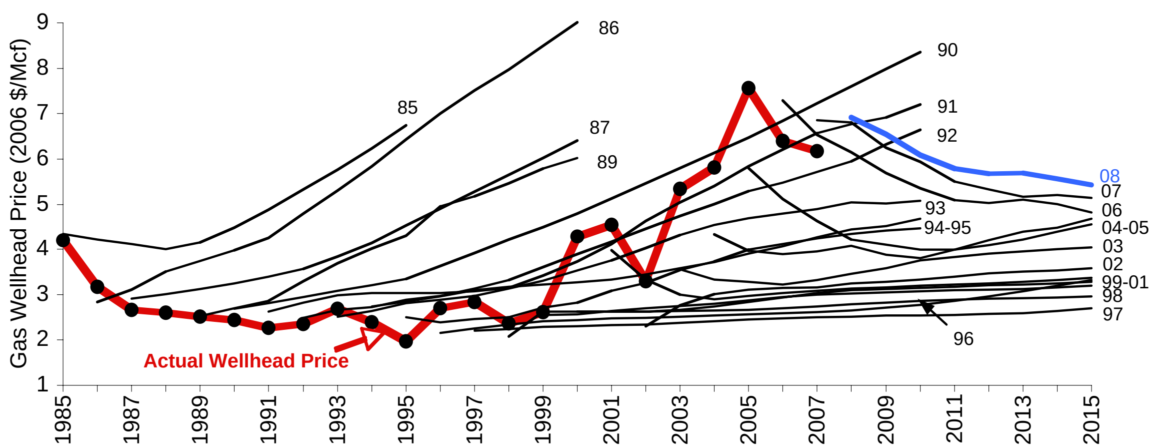
Finally, it should be noted that working within an uncertainty framework allows for extension of typical forecasting to consider real options and other techniques derived from portfolio theory (Awerbuch 2003, Siddiqui 2007).

## The Importance of Uncertainty

The type of forecasting conducted in support of policymaking and planning in the U.S. has typically paid scant attention to the significant uncertainty inherent in many aspects of such analysis. Forecasts are frequently presented as point estimates only, or as point estimates with sensitivity cases or side scenarios.[2] A preeminent example of the point forecast with side scenarios is the AEO.

Despite the obvious importance of uncertainty in any forecasting endeavor, the stability of conditions in the later part of the twentieth century fostered complacency. Figure 1 shows the AEO forecasts of wellhead natural gas prices. The years in which the forecasts were made are shown, as is the actual trajectory of prices to date. Notice that the forecasts change year-by-year towards the extrapolation of recent prices. Additionally, while some forecasts featured falling prices followed by an upswing, of the 23 forecasts displayed, only the ones made around 1990-92 came close to identifying the key turning point that occurred around 1995. Finally, conduct the mental exercise of extrapolating the outer boundary of 1985 and 1997 forecasts out to 2050. The range of possible forecasts contained in those boundaries is vast, and these are not representations of uncertainty per se, they are actual point forecasts, just made in different eras.

**Figure 1. EIA Forecasts of Natural Gas Price**




source: EIA 2008 & 2008a, AEO from several years

In addition to the unpredictability of technology evolution, there are several common aspects to how uncertainty enters into a forecast, and most of them are familiar and intuitive: inaccuracy of historic data, errors in methods, unexpected external conditions, price volatility, etc. All of these argue for modeling the future with key scalar variables replaced by probability distributions that reflect our level of confidence in our forecasts of their values. Such an approach is the simple principle by which SEDS is being constructed on a platform specifically intended for such modeling, Analytica®, developed by Lumina Decision Systems.[3]

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[2] In general, a sensitivity case is a rerun of an analysis in which just one input is changed, while a scenario is one with multiple variables adjusted.

[3] Analytica® has been developed over many years by Max Henrion, the founder of Lumina, and others. Its genesis was software developed by Henrion when he was a professor at Carnegie Mellon, and he also coauthored the classic text on considering uncertainty in policy analysis (Morgan and Henrion 1990). Analytica® is specifically intended for model building of the SEDS type. For more information, see http://www.lumina.com/

Before exploring SEDS, it is worth noting a key aspect of forecasting that SEDS does not address. Energy history may have turned a corner around the same time the millennium turned. A long period of relative stability that lasted from the mid-1980's appeared to come to an abrupt end. Fuel prices became more volatile and have generally increased, raising overall costs. Note that introducing uncertainty into certain variables does not imply that we can produce forecasts that include discontinuities, and indeed, these might be the events forecasters would be most interested in predicting. Rather, the SEDS approach provides a wide distribution around forecasts to reflect the uncertainty of point forecasts. Nonetheless, SEDS estimates and their uncertainty bounds are still highly smoothed curves, and any "corners" can only be introduced by the modeler (Short et al. 2007 and Siddiqui 2007).

## Structure of SEDS

Similar to NEMS, the architecture of SEDS is that all energy producing and consuming activities in the economy are modeled using a set of interconnected modules representing the key sectors, where the inputs to one module are the outputs from others (SEDS 2008). Planned or existing SEDS modules are currently called Macroeconomic Activity, World Oil,[4] Coal, Natural Gas, Renewable Fuels, Liquid Fuels, Transmission, Electricity, Industry, Buildings, and Transportation. Also like NEMS, SEDS uses energy and capital costs to determine economically optimal technology adoption. Unlike NEMS, SEDS Lite is designed to favor simplicity over detail, with the goal of providing a system that produces results quickly out to 2050. SEDS does not iterate towards an equilibrium, rather outputs of one time step are inputs to the next, and an effort is being made to keep the modules consistent enough for users to delve into them. Also, to allow user control over runtime, SEDS is designed around a variable user-chosen time step. Note that the emphasis on fast execution time is motivated by the need to achieve stochastic results with acceptable variance reduction. The details of interconnection and calibration between the modules have not been fully worked out, and the modules themselves are in varying states of completion. The SLBM is among the most well developed and can be run in a stand alone mode in a test harness that provides it with the necessary inputs, including energy prices, Gross Domestic Product (GDP), population, and other macroeconomic inputs.

## Generic SEDS Template

In the spirit of developing a tool that is relatively easy to program and with the goal of transparent logic, an early SEDS team decision was to develop a standard module *Template* that encapsulates the core logic of engineering-economic decision-making that could be used in every module. The Template is basically a code library that standardizes the process of defining and quantifying service demands, such as annual kWh of domestic hot water (DHW), to be met with specific technologies using a logit market segmentation. It also standardizes the data input to characterize each technology (lifetime, performance, unit costs, etc.) and the calculation of its market share at each time step. The Template assumes that there is a stock of existing equipment, then the logit market share calculations are used to determine what new equipment is chosen to

[4] All modules except World Oil are at the U.S. national level.

meet expanding and replacement requirements. Consumption rates of fuels at each time step are calculated by determining how much fuel is required to operate the stock of existing equipment to exactly meet the service demands. Thus, the Template, and SEDS generally, can be thought of as a systems or stock model (see Chapter 1 of Hannon and Ruth).

There are clearly benefits to the simplifying assumptions of the Template and the standardization it provides; however, fitting it to any of the energy sectors inevitably creates problems, and buildings are no exception. First and foremost, the Template was designed to trade-off the attributes of similar technologies for meeting a single service demand. For example, all else being equal, it chooses a more efficient refrigerator over a less efficient one to meet requirements for refrigeration service; however, many of the best examples of energy saving potential in buildings do not fit the pattern of simple efficiency improvements to existing technology. Such examples are better thought of as changes of approach, e.g. passive reduction in active service requirement versus more efficient active systems for meeting requirements. Inevitably, the trade-off between the convenience of a common module structure and representing the details of a sector proves tricky. One of the fundamental issues with the buildings sector is that radical changes in service provision might be necessary to meet climate change goals, but some of the immediate problems encountered in the SLBM include the following:

- a major research area for buildings concerns whole systems design, commissioning, and operation that takes advantage of several components working together to create mutual benefits and sometimes eliminates equipment, which is technically dissimilar to single service technologies, such as vehicles;
- passive approaches, such as insulation, daylighting, and building orientation, provide tangible building services but consume no energy directly and often augment the effects of mechanical systems;
- internal heat gains decrease the demand for heating in winter and in large commercial buildings in some climates are the dominant source of cooling demand in the summer, and these effects confound rigid concepts of energy services;
- on-site generation of electricity that offsets external electricity purchase without reducing consumption by on-site appliances requires site-specific economic evaluation, and in some cases, co-produces waste heat that can off-set other building energy requirements;
- tastes for provision of services in buildings could change radically, e.g. a preference for smaller homes might emerge, or similarly, exogenous forces could influence building design choice, e.g. changing available home mortgage options.

Many of the best strategies for lowering net energy use by buildings fall into this list. On top of this, climate has a major effect on the service demands to be met within a given building, so service demands were estimated for 9 climate zones, although results are only reported nationally.

## Implementation of the Buildings Module

The residential and commercial sectors in the SLBM can be thought of as a series of stock models running in parallel that track equipment characteristics and market share as time progresses. The stock of equipment required is determined by the overall demand for its services, e.g. lum·h/a. At each time step, a series of calculations are performed that take input macroeconomic data and fuel prices and output estimates of fuel consumption requirements for provision of a set of building services, i.e. lighting, DHW, ventilation, refrigeration, other loads, heating, and cooling. Those calculations are performed as follows (see also Figure 2):

(1) The total demand for floorspace for residential and commercial buildings is forecasted using a simple linear multivariate econometric regression model (described in more detail below) with the following independent variables: GDP, population, a time lag, and disposal personal income (DPI).[5]
(2) A building stock model determines required new construction at each time step to meet floorspace demand. The floorspace stock model also tracks demolition based on average building lifetimes.
(3) Current floorspace is multiplied through by the expected service demand intensities to arrive at the total raw service demands. In the case of heating and cooling, floorspace is disaggregated by climate region so that heating and cooling degree days (HDD & CDD) can serve as appropriate service intensities.
(4) The total raw service demands are adjusted for the influence of passive technologies, such as insulation and daylighting, as well as other mitigating factors, such as internal heat gains and infiltration.
(5) The residual service demands are passed on to specific stock models as these must be met by active, i.e. fuel consuming, technologies.
(6) Every service-specific stock model tracks the amount of each technology available at each time step considering retirements, and calculates how much new equipment will be needed.
(7) The amount of each type of new equipment put into service is determined by an engineering-economic calculation using a logit function to determine market shares. The current logit parameters are somewhat arbitrary, and we are actively seeking to improve this aspect of the SEDS Template.
(8) Fuel type, efficiency, and technology market share are then used to determine total fuel consumption.
(9) Fuel consumption is then offset by on-site generation with or without combined heat and power as appropriate (this capability is in development).
(10) Fuel consumption is summed across all demand-specific stock models to yield total fuel demands.
(11) Finally, residential and commercial fuel demands are summed to total SLBM fuel consumption.

After the sequence defined above has been executed for each time step, the projections of floorspace, service demands, technology market share and quantities, energy consumption and fuel use are available for examination and interpretation; however, if any of the macroeconomic or other inputs are based on a probabilistic distribution rather than scalar values, the model runs multiple times with Monte Carlo draws.

[5] Note that SEDS has a Macroeconomic Module to forecast these parameters, and there is also a harness that includes the values used in NEMS.

## Passive Characteristics in Buildings

Given the strengths of the Template in modeling stocks of single-service, single-fuel technologies, it was adopted for this purpose within many parts of the buildings module. Nonetheless, some of the most promising future building efficiency developments rely on improving system integration and passive designs; therefore, much of the challenge and effort in SLBM development was the creation of a framework that could capture these alternative paths while still providing quick run-times and a transparent structure for users. Two particular objectives were crucial in shaping the SLBM:

(1) to accommodate technologies that do not consume fuel, e.g., windows, but strongly affect multiple other energy consuming technologies; and

(2) to recognize interactions between end-uses, particularly the heat gains from lights and electrical equipment that are sometimes more important than envelope losses in determining the heating and cooling requirements of commercial buildings, and also play a significant and growing role in residential buildings.

**Figure 2. Main SLBM Calculation Steps *(T represents a copy of the Template.)***

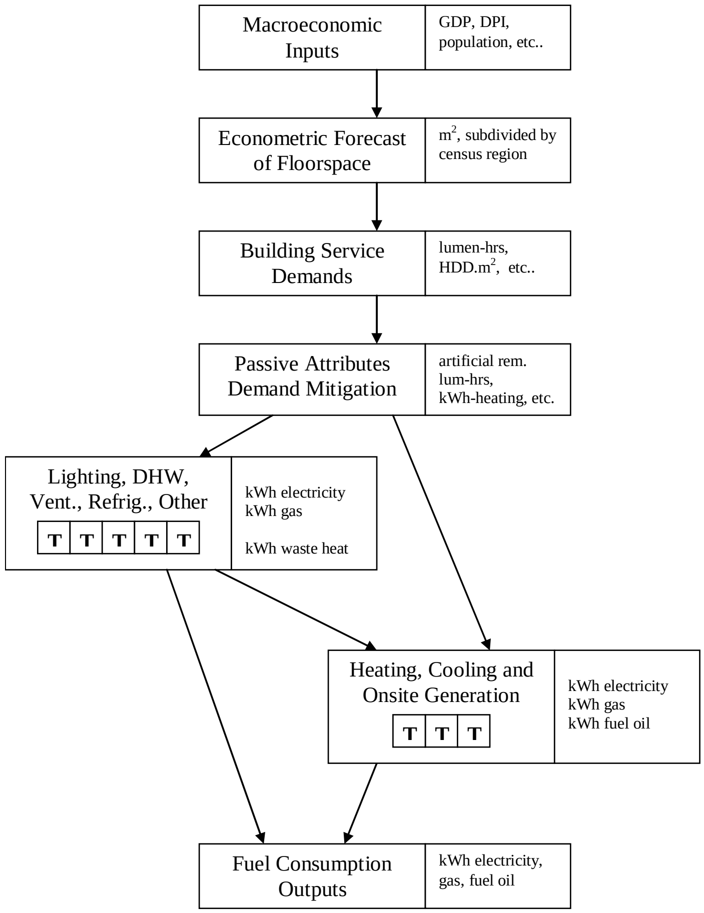



Figure 2 shows the basic structure that is used in both the residential and commercial sub-modules. The *Passive Attributes* sub-module considers the aspects of the building shell that meet, mitigate, or intensify the heating, cooling, ventilating, and lighting service requirements. The elements in this sub-module are special in that they do not consume any fuel, and in that they are described by a vector of properties, e.g. daylighting effectiveness, natural ventilation effectiveness, solar gain intensities in heating and cooling seasons, and the envelope heat-transfer intensities in the heating and cooling seasons. The two sub-modules which follow use copies of the Template to determine equipment choice between available technologies for each service, with each technology meeting a single service. The sub-module denoted *Lighting, DHW, Ventilation, Refrigeration, Other* addresses technologies meeting these end-uses, and calculates the internal heat gains generated by them. The *Heating, Cooling and On-site Generation* sub-module uses these internal heat gains, along with the passive attributes of the building shell to determine the heating and cooling load that must be met by active technologies, and also will consider options for buildings to self-provide some of its energy requirements.

## Floorspace Forecast

Two commercial floorspace models and one residential model were fit by stepwise regression to historic data for this purpose (PNNL 2006). For the commercial sector, the highest adjusted $R^2$ of 0.975596 was achieved using a model with a one-year time lag; however, this time lag creates a timing problem because SEDS must run on different time steps, i.e., 0.5 year, 1 year, and 2 years, at a minimum, requiring multiple models.[6] As shown in Table 1 the highest adjusted $R^2$ can be reached by using a time lag of one year. The corresponding t-statistic is very significant, 42.45, and the time lag is the most significant explanatory variable. A time lag of two years is not as significant and omitted. For every time step in SEDS that is less than one year or higher than one year, the model with no time lag and adjusted $R^2$-value of 0.975569 is used.

**Table 1. Used Econometric Commercial and Residential Floorspace Models**

| | model | adjusted $R^2$-value | coefficients / t-statistics |
|---|---|---|---|
| Commercial, time lag of one year | $F_t = C_1 F_{t-1} + C_2 POP_t + C_3 GDP_t$ | 0.97559559 | $C_1$ = 0.945436 / 42.45; $C_2$ = 0.001188 / 3.77; $C_3$ = 0.0000155 / 2.18 |
| Commercial, no time lag | $F_t = 0 + C_2 POP_t + C_3 GDP_t$ | 0.97556915 | $C_1$ = nA / nA; $C_2$ = 0.014364 / 39.41; $C_3$ = 0.0003059 / 22.77 |
| Residential | $\ln FR_t = C_2 POP_t + C_4 \ln DPI_t$ | 0.95994454 | $C_2$ = 0.005712 / 21.31; $C_4$ = 0.152549 / 19.08 |

$F_t$ commercial floorspace in year t [$10^9$ $m^2$]
$F_{t-1}$ commercial floorspace in year t-1 (time lag of one year) [$10^9$ $m^2$]
$POP_t$ population in year t [$10^6$]
$GDP_t$ U.S. Gross Domestic Product in year t [\$$10^9$, chained (2000)]
$C_1$ Lag coefficient
$C_2$ POP coefficient
$C_3$ GDP coefficient
$FR_t$ residential floorspace in year t [$10^9$ $m^2$]
$DPI_t$ disposal personal income total [$10^9$ dollars, chained (2000)]
$C_4$ coefficient for DPI

## Tracking Building Stock

**Equation 1.**

$$Survival\ Rate = \frac{1}{1 + \left( \frac{y - y_0}{Average\ \ Lifetime} \right)^{\gamma}}$$

$y$: year, $y_0$: year of construction

Because shell integrity is assumed to be different between existing and new buildings, it is important to segregate floorspace accordingly. Estimates of projected commercial and residential floorspace include additions, assumed to be the difference between the surviving

[6] It should be noted that some of the historic data points are estimated, which is legitimate for forecasting purposes, but the importance of $R^2$ should not be overblown.

floorspace and the total floorspace requirement forecast by the preceding econometric equations. Over time, the existing stock declines as buildings are demolished, estimated by a logistic decay function, the shape of which depends upon two parameters, mean building lifetime and the parameter $\gamma$, which corresponds to the rate at which buildings retire near their median expected lifetime (see Equation 1). Average Lifetime and $\gamma$ are based on the commercial demand module documentation from NEMS (EIA 2007). Based on this data set, the average lifetime of commercial buildings is assumed to be 73.5 years, and $\gamma$ is 2.0. The resulting decay function and building stock compostion are depicted in Figures 3 and 4. The latter shows the breakdown between pre and post 2005 construction, with the 2050 stock roughly equally split between them.

**Figure 3. Building Survival Function for Commercial Floorspace**

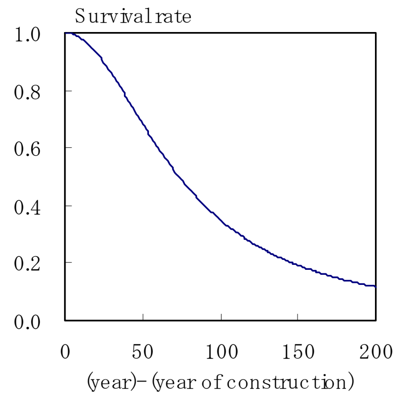
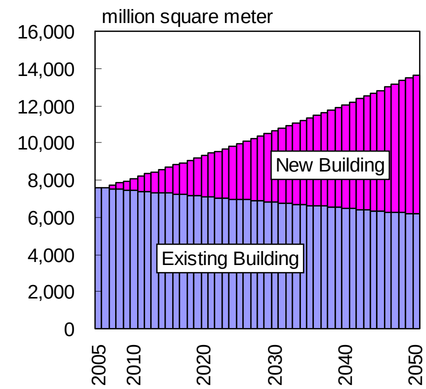



**Figure 4. U.S. Commercial Floorspace Area Calculated by SLBM**




## Data Sources

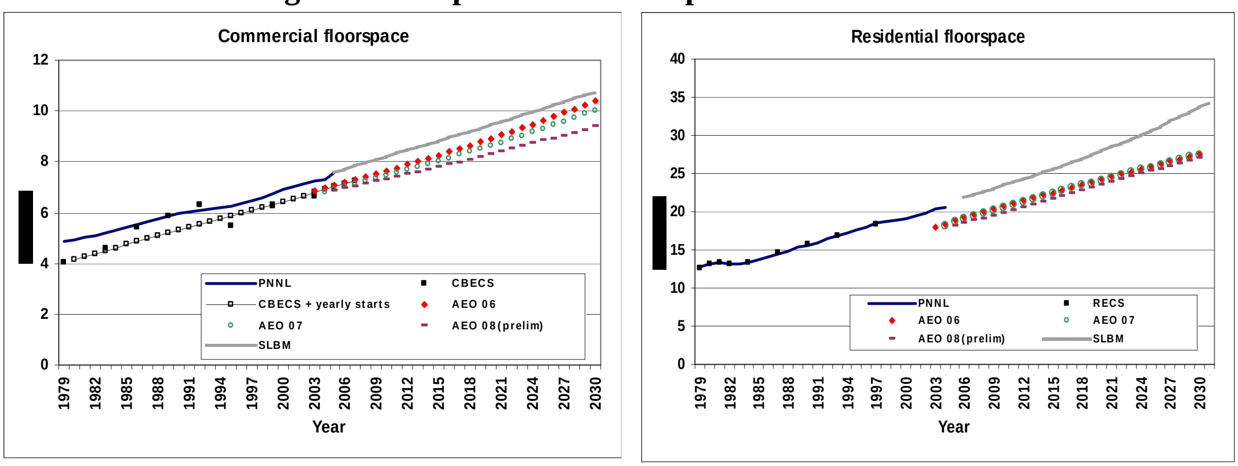
Historical floorspace input data are based on PNNL's commercial and residential energy intensity indicators, which in turn are based on EIA's Commercial Buildings Energy Consumption Surveys (CBECS) and Residential Energy Consumption Surveys (RECS). Figure 5 compares several forecasts, including the SLBM's, of commercial and residential floorspace. For commercial floorspace, an additional comparison has been plotted which incorporates data from McGraw-Hill Corporation's Construction Analytics. Construction Analytics data provides historical building construction *starts* information, i.e. how many buildings, what types, total square meterage, etc. (F.W. Dodge 1991). When the yearly starts are added to the 1979 CBECS, the resulting commercial floorspace plot shows a fitted curve for all of the subsequent CBECS years as well as a match with AEO projections.

The SLBM forecast tends to be higher than AEO forecasts, due to differences in building definitions; however, for calculation of the specific service demands, e.g. lum·h/$m^2$, the SLBM forecast is used, thereby eliminating any discrepancies. The final energy demand data, obtained from PNNL, CBECS, RECS as well as the Annual Energy Review (AER) for 2005, for each fuel were divided by the SLBM floorspace estimates for 2005 and used for service demand forecasting. Equipment types were considered for refrigeration, space cooling, space heating, lighting, water heating, and ventilation. All other end-uses were categorized as plug loads. The installed equipment stock information is based on Berkeley Lab's own calculations derived from appliance manufacturers' shipments data, CBECS (CBECS 2007), RECS (RECS 2001), and AEO-07 (EIA, 2007a).

## Early Results

The SLBM is in an early stage of testing and evaluation. Comparisons between the Annual Energy Outlook 2007 (AEO-07), which is based on NEMS and SLBM have been performed. Figure 6 shows the SLBM final energy results as well as the AEO-07 forecasts for total natural gas demand through 2030. However, the initial values are heavily influenced by a market share estimate for the various technologies satisfying the initial energy demand. Especially, these market shares for the first simulation year (= initial value) are a dominant factor and difficult to estimate because information is mostly available for shipments, which have to be translated to energy usage as needed for SLBM.

**Figure 5. Comparison of Floorspace Data and Model Results**




source: CBECS, RECS, PNNL, McGraw-Hill Construction Analytics history, AEO and SLBM forecasts

**Figure 6. Comparison of AEO-07 and SEDS Expected Values for Total Natural Gas Demand (All Buildings)**

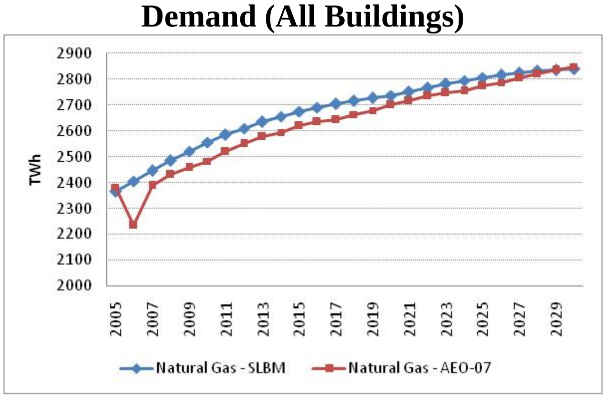
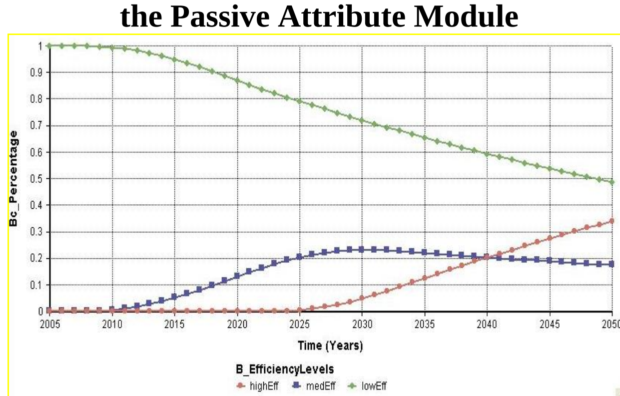



**Figure 7. Market Penetration of Low, Mid, and High Efficiency Buildings Imposed by the Passive Attribute Module**



As can be seen from Figure 6, the SLBM natural gas demand levels off around 2030. The major reasons are internal heat gains (see also Figure 8), which reduce the heat load and the higher building quality for new buildings as set by the passive attribute module (see Figures 3 and 7, and the section *Tracking Building Stock*). The biggest advantage of SEDS is its stochastic nature. For example, Figure 9 shows the min, mean, and max adoption of high Annual Fuel Utilization Efficiency (AFUE) gas heating systems for the commercial sector based on an arbitrary triangular distribution of (-0.05, 0, +0.05). The next important steps in SLBM development will be to add triangular functions reflecting real world uncertainty about the outcome of technology development under way by USDOE.

**Figure 8. Comparison of SLBM and AEO-07 results for natural gas heating in the commercial sector**

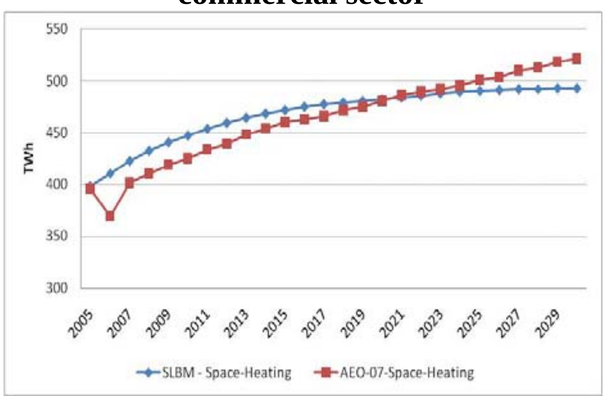
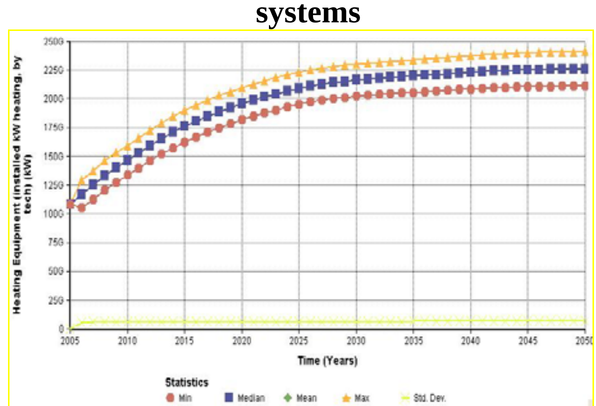



**Figure 9. Stochastic results from SLBM for installed high AFUE gas heating systems**




## Conclusions

Anticipating how current R&D should be directed to robustly meet the climate change challenge, especially given wide uncertainty about our evolving energy system, creates a formidable modeling challenge. USDOE is attempting to respond through the creation of an uncertainty based forecasting tool, SEDS. The buildings aspect of this tool will be mixture of innovation and tradition. Floorspace forecasting is based on a regression of macro variables against historic floorspace requirements. Downstream of this calculation, the model attempts to use building service requirements rather than energy-based metrics of services as the basis of equipment adoption and energy use forecasts. These service requirements are in turn connected to the composition of the existing building stock. Actual equipment choice is constrained within a common Template that applies to all sectors. The goal is to represent decision-making such that active, passive, and on-site energy conversion options are evenhandedly considered in a way that might allow for radical rethinking of building design and therefore R&D objectives and investments.

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