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Methodology for Analyzing the Technical Potential for Energy Performance in the U.S. Commercial Buildings Sector with Detailed Energy Modeling

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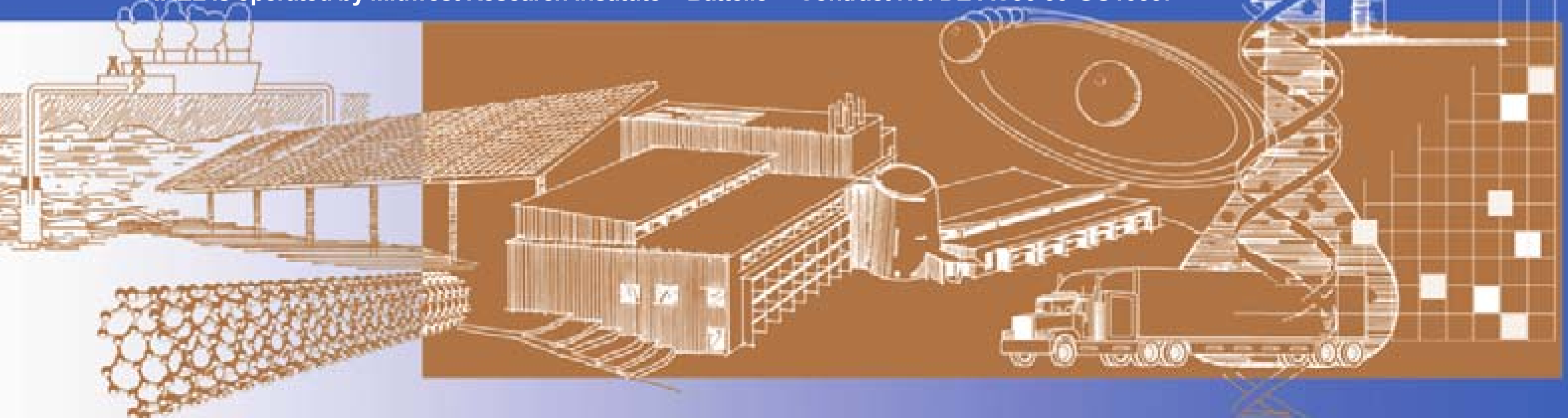

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METHODOLOGY FOR ANALYZING THE TECHNICAL POTENTIAL FOR ENERGY PERFORMANCE IN THE U.S. COMMERCIAL BUILDINGS SECTOR WITH DETAILED ENERGY MODELING[I]

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ABSTRACT

This paper summarizes a methodology for developing quantitative answers to the question, "How low can energy use go within the commercial buildings sector?" The basic process is to take each building in the 1999 CBECS public use data files and create a baseline building energy model for it as if it were being built new in 2005 with code-minimum energy performance. The 1999 CBECS data form a statistical model of the commercial buildings sector by using a set of 5,430 buildings with weighting factors to indicate how many more such buildings are represented by each member. For each building, we used 1999 CBECS data on floor area, number of floors, census division, basic climatic design criteria, principal building activity, and number of employees. The expanded building descriptions needed for detailed energy modeling with EnergyPlus were generated by applying ASHRAE Standard 90.1-2004 and augmenting with data from Huang and Franconi (1999), probabilistic assignments, and other assumptions. The technical potential of energy design measures, for the sector as a whole, were then evaluated by altering and rerunning the energy models, comparing perturbed results to each baseline, and then aggregating performance metrics. The primary benefit of the method is that the CBECS weighting factors provide a robust way of aggregating national results from simulations of individual buildings. However, it is also challenging because it requires considerable computing resources. The methodology is recommended for future analyses when the results must properly reflect the national implications and when only a limited number of scenarios need to be investigated.

INTRODUCTION

Buildings can be designed in such a way that a thorough application of energy-efficient design practices and technologies combined with photovoltaic (PV) on-site electricity generation might convert them from energy consumers to energy producers. The net-zero point, where as much energy is produced as used each year, lies at the heart of one definition of the zero-energy building (ZEB) concept. Choosing PV for on-site energy production is appealing, since the roofs of virtually all commercial buildings could be considered viable sites and PV systems have little adverse impact on buildings.

The U.S. Department of Energy's (DOE) Building Technologies (BT) program set a goal of creating the conditions for low- and zero-energy commercial buildings (LZEBs) to be market viable by 2025. However, such a goal is realistic for only a portion of the commercial sector, since some commercial buildings are far too large and power hungry to meet all their energy needs with on-site solar power. This begs two questions: What portion of the commercial sector could actually reach the ZEB goal? And how low can you realistically go across the sector as a whole?

This paper describes a methodology for studying such questions by assessing the technical potential of sets of energy improvement technologies and practices in the commercial buildings sector. We use the term *technical potential* to refer to "maximum technology" scenarios that are used to estimate the limits of what is possible in the sector. As such, we do not include cost and economic analyses such as assessing market penetration or projecting how the sector might evolve. This technical potential study looks at what could

[I] This work has been authored by an employee or employees of the Midwest Research Institute under Contract No. DE-AC36-99GO10337 with the U.S. Department of Energy.

happen if all the buildings were changed at once and does not track rates of adoption or model additions and retirements of the building stock. We focused on evaluating sets of known technologies and practices and modeling the system interactions with detailed engineering calculations. For this study, the authors used EnergyPlus (Crawley et al. 2001) to model the energy performance of a variety of commercial buildings in various subsectors and climates.

Whole-building energy performance modeling has been in use for approximately 30 years, and researchers have used such tools to represent large portions of the building stock. Some of the earliest studies were conducted by researchers at Pacific Northwest National Laboratory (Briggs, Crawley, and Belzer 1987; Briggs, Crawley, and Schliesing 1992; Crawley and Schliesing 1992). A more recent example is research by Huang and Franconi (1999) at Lawrence Berkeley National Laboratory, who built on this work. Moffat (2001) presents a good overview of these methods, which he refers to as stock aggregation, in the context of life cycle analysis and community planning. Moffat equates such bottom-up methods with "normative futures analysis" and "backcasting." Large-scale simulation studies are also common in the history of developing and evaluating codes and standards.

This paper presents a brief overview of a methodology for evaluating energy performance across the entire U.S. commercial buildings sector. An implementation of the methodology is described and sample results are presented from an evaluation of the potential for U.S. commercial buildings to reach a goal of annual net-zero site energy use.

METHODOLOGY

The methodology can be divided into two separate modeling domains: (1) the modeling used to describe the sector; and (2) the modeling used to describe individual buildings.

Sector Modeling

A national sector model is a set of building types, locations, and weighting factors. Each member of the set is a model of a single building that can be analyzed in detailed (forward) building energy modeling tools. The sector model is key to connecting annual energy modeling tools to national assessments of the sector-wide performance potential. The national sector model used here is based on a large (N = 5,375) set of building models that was derived directly from a robust statistical data set developed by the U.S. Department of Energy's Energy Information Agency (EIA).

The EIA statistical data set used here is known as the *1999 Commercial Buildings Energy Consumption Survey* (CBECS) Public Use Data (EIA 2002). The basic process is to take each building in the 1999 CBECS public use data files and create a baseline building energy model as if it were being built new in 2005 with code-minimum energy performance. The 1999 CBECS includes data on 5,430 buildings and provides weighting factors to indicate how many more such buildings are represented by each entry to form a statistical model of the commercial buildings sector. For each building, we used CBECS data on floor area, number of floors, census division, basic climatic design criteria, principal building activity, and number of employees. We then augmented descriptions needed for simulation by a number of assignments based on building standards for commercial buildings to represent new stock. A key assumption here is that the CBECS weighting factors are still applicable, although many details of the survey buildings are unknown (to the public) and therefore need to be generated synthetically. These details are part of the building modeling domain discussed below. We also assume that the mix of buildings in the sector will not change over the years and that the same weighting factors will be used for future scenarios. The sector model used here excluded refrigerated warehouses, so the total number of baseline building models was 5,375 (down from 5,430 in 1999 CBECS).

The primary benefit of basing the sector model directly on CBECS is that the weighting factors (the variable `ADJUST7`) provide a robust way of obtaining national results from models of individual buildings. For example, to aggregate results for the national average for percent savings in net site energy use intensity (*netEUI* or *E*) for a particular LZEB scenario, we use the weighting factor and floor area data from CBECS in the following manner:

$$\%\,\text{savings} = \frac{\left(\left(\dfrac{\sum_{i=1}^{N}\left(E_{i,base}A_iW_i\right)}{\sum_{i=1}^{N}\left(A_iW_i\right)}\right)-\left(\dfrac{\sum_{i=1}^{N}\left(E_{i,LZEB}A_iW_i\right)}{\sum_{i=1}^{N}\left(A_iW_i\right)}\right)\right)}{\dfrac{\sum_{i=1}^{N}\left(E_{i,base}A_iW_i\right)}{\sum_{i=1}^{N}\left(A_iW_i\right)}}\cdot 100 \qquad (1)$$

where,

i is the index for each individual model,

E is the net energy use intensity,

N is the total number of model results,

A is the building floor area, and

W is the weighting factor.

To determine the fraction of commercial floor area that could reach the ZEB goal, we use the following:

$$Fraction\ ZEB = \frac{\sum_{i=1}^{N} \begin{pmatrix} A_i W_i & if\ E_{i,LZEB} \leq 0.0 \\ 0.0 & if\ E_{i,LZEB} > 0.0 \end{pmatrix}}{\sum_{i=1}^{N} \left(A_i W_i \right)} \quad (2)$$

Such summations can also be performed over subsets of N to characterize portions of the sector to differentiate by characteristics such as principal building activity, geography, number of floors, and floor area. The aggregations are also a practical method of simplifying the results from large numbers of models.

Building Modeling

Defining a building model for detailed, whole-building energy modeling programs, such as EnergyPlus, requires considerable detail. Table 1 lists examples of input parameters that are used to structure these myriad details into the following four categories:

Program refers to the *architectural program*, which describes how the building will be used and the services it must deliver to the occupants. From an energy point of view, the program influences many important drivers (climate, plug and process loads, ventilation requirements, operating schedules, and comfort tolerances) that will ultimately determine energy performance.

Form refers to the geometry of the building and its elements, and has important energy implications that stem from how the building interacts with the sun and ambient conditions.

Fabric refers to the materials that are used to construct the building and involves insulation levels, glazing systems, and thermal mass.

Equipment includes HVAC equipment and lighting systems and controls. Except for plug and process load equipment selected by the occupants, this includes all the energy-consuming equipment that is part of the building.

Table 1 Input parameter categories

PROGRAM	FORM	FABRIC	EQUIPMENT
Facility location Total floor area Schedules Plug and process loads Lighting levels Ventilation needs Occupancy Site constraints	Number of floors Aspect ratio Window fraction Window location Shading Floor height Azimuth	Exterior walls Roof Windows Interior partition Internal mass	HVAC system types Component efficiency Control settings Lighting fixtures Lamp types Daylighting controls

Inputs such as those listed in Table 1 are considered "high-level" parameters, which do not, or cannot, appear directly in the input file. These parameters often imply a one-to-many relationship and that rules are needed to translate the parameter to multiple model input values. High-level parameters can directly represent an energy design measure separately from how that measure needs to be represented to the simulation program. In this methodology, the focus of the building modeling domain is to manage how the high-level parameters are determined and then mapped to the low-level inputs that are needed for detailed energy modeling programs such as EnergyPlus.

Available data in 1999 CBECS are quite limited in contrast to the detailed input needed for energy models. This (and the fact that BT's ZEB goal mainly addresses new construction) led to a fundamental shift where the CBECS statistical model for existing stock was used as a proxy for a statistical model of the types of buildings being built in 2005. So instead of the real building, we used ASHRAE 90.1-2004 to help define many important features that govern energy use for fabric and equipment. Table 2 presents a summary of the sources used to assign values for key input parameters.

CBECS masks the locations of buildings for anonymity in the survey, but does provide data for the census division (`CENDIV7`) and values for heating degree-days (`HDD657`) and cooling degree-days (`CDD657`). The location assignment algorithm used here compares these reported degree-day values to the degree-days for all the weather locations (with typical year weather data) in that census division and chooses the one with the closest match. The building is then assigned to this weather location.

Table 2 Assigning model details

PARAMETER	SOURCES
Location and Weather	Fit degree-day and Census Division data from CBECS
Utility tariffs	Gas:EIA; Electricity: TAP and utility web sites
Envelope construction	ANSI/ASHRAE/IESNA Standard 90.1-2004
Floor area and number floors	1999 CBECS public use data
Aspect ratio and azimuth	Probabilistic assignments
Glazing fractions	Huang and Franconi 1999; assumptions
People density	Number of worker data from 1999 CBECS; ANSI/ASHRAE/IESNA Standard 90.1-1989
Lighting power density	ANSI/ASHRAE/IESNA Standard 90.1-2004
Plug/process power density	Assumed mean by activity type, probabilistic assignments
Schedules	Modified versions from ASHRAE Standard 90.1-1989
Outside Air Ventilation	ANSI/ASHRAE Standard 62.1-2004

Modeling the energy cost implications for commercial buildings also requires that demand charges be calculated and tariff schedules be changed based on service capacity. A comprehensive data set of utility tariffs is needed to implement this methodology. Such a data set was developed that contains input objects for 120 tariffs for 40 utility companies by synthesizing data from EIA, a Web-based central repository run by the Tariff Analysis Project (TAP) (http://tariffs.lbl.gov/), and utility company Web sites.

The methodology also uses (pseudo) random number generation to capture much of the variability in buildings. We used probabilistic assignments (by applying the central limit theorem) to create many details such as distribution of plug and process loads, azimuth and aspect ratio, and infiltration. For plug and process, or interior electrical equipment, we assumed a normal distribution, and values for the mean and standard deviation of the peak power density. For azimuth and aspect ratio, we assumed a uniform distribution.

Huang and Franconi (1999) provide values for glazing fractions for selected types of new-vintage buildings. These were used and then augmented with assumptions for building types that were not covered.

1999 CBECS provides data on the number of workers (NWKER7), the total square footage (SQFT7), and various numbers for capacities (RWSEAT7, PBSEAT7, EDSEAT7, FDSEAT7, and HCBED7). ANSI/ASHRAE/IES Standard 90.1-1989 Section 13 also provides recommendations for occupancy density. To determine occupancy levels, we used the number of workers specified in 1999 CBECS—except where nonemployees as well as employees would be expected to be in the buildings—in which case we used Standard 90.1-1989.

The methodology also requires sets of schedules that are common in energy modeling. ANSI/ASHRAE/IES Standard 90.1-1989 Section 13 includes schedules for use with the Energy Cost Budget method. In Standard 90.1-1989 (with addenda) the lights and equipment shared the same schedules, but case study research and broad anecdotal evidence suggest that plug and process loads do not necessarily track lighting loads and that during off hours they are higher, probably because of increased use of information technology and security equipment. Therefore, new plug and process schedules were created, by assumption, for use with this methodology. These have nighttime levels that are 20%−40% of daytime, depending on activity.

Once the values for high-level parameters are obtained (from CBECS and other sources), then rule-based algorithms are needed to define exactly how each building is modeled from a set of high-level parameters. For such large numbers of models, preprocessing routines are needed to automatically generate complete input files for the modeling program. The main task of the preprocessor is to translate the high-level parameters into a description of the building geometry and combine that with all the other data needed to run a simulation. Geometry auto-building of "shoebox" buildings is common in energy modeling and is applicable here. The preprocessor needs to implement various transformations, including thermal zoning, HVAC system configuration and operation, overhang creation, and the use of multipliers to reduce simulation execution time for buildings with large numbers of floors or large numbers of fenestration components.

EXAMPLE RESULTS AND DISCUSSION

The methodology described above was applied to a study of how achievable the goal of net zero is in the commercial sector. Algorithms for performing assignments were developed and implemented in a preprocessor.

Using a large set of models addresses the problem of how to credibly assess the sector as a whole, but it also presents severe technical challenges for how to deal with tens of thousands of simulations and the demand for computing resources and data management. These challenges were handled by constructing custom software that includes automatic creation of EnergyPlus input files, database and routines for dispatching and executing models on a large Linux cluster, mining EnergyPlus output files for results and storing them in a database, retrieving results from the database, and reducing and analyzing results into manageable forms for reporting. We used a 64-bit compiler for Linux to compile EnergyPlus and make efficient use of a large cluster.

A few results from a study that used the current methodology are presented here for these four scenarios:

1. **Base** produced reference baseline results by applying ANSI/ASHRAE/IESNA Standard 90.1-2004 to define characteristics that affect energy performance.
2. **Base w/PV** examined how effective it would be to only add PV to the baseline buildings. The systems applied 10% efficient PV panels with an area equal to 50% of the total roof area for every building. The same PV systems are used in the LZEB 2005 scenario.
3. **LZEB 2005** examined what can be achieved when an aggressive package of currently available technologies and practices is applied. Each building was reoriented and elongated along an east-west axis for good daylighting and passive solar design. Exterior fixed overhangs were added to south-facing glazing. Tubular daylighting devices were added to core zones. ZEB technologies for the facade were modeled by adding superinsulation and superwindows. The HVAC system was changed to a centralized, chilled-water-based variable air volume system with economizer and heat recovery ventilation on the outside air system. Lighting power density (LPD) was reduced 17% from ASHRAE 2004 by assuming the use of super T8 lighting. The coefficient of performance (COP) of all water-to-water chillers was set at 6.0. Gas heating efficiency was raised from 80% in the baseline models to 95% by assuming the use of condensing boilers.
4. **LZEB 2025** predicted the energy savings with all the same measures as the LZEB 2005 scenario with somewhat higher component performances than are currently available, but that would seem to offer reasonable outcomes after 20 years of R&D. This scenario includes a doubling of the efficiency in rooftop PV panels and a slight improvement in inverter efficiency. LPD levels were reduced by 50% from ASHRAE 2004. Chiller COP increased from 6.0 to 6.5 (by assumption), and heating efficiency increased from 0.95 to 0.97 (by assumption). Fan static pressure decreased slightly, and minor improvements in HVAC systems are forecast.

ZEB Potential

We used Equation 2 to evaluate the results for the three alternative energy performance scenarios and to determine how much of the commercial sector could reach the ZEB goal. The results are shown in Figure 1. The ZEB goal was found to be achievable for portions of this sector—with 2005 technologies and practices, 22% of commercial buildings could reach net zero. Projections for technology improvements by 2025 increase this percentage to 64%. Calculated according to floor area, rather than by number of buildings, the percentages that can reach the ZEB goal are 23% for 2005 and 53% for 2025.

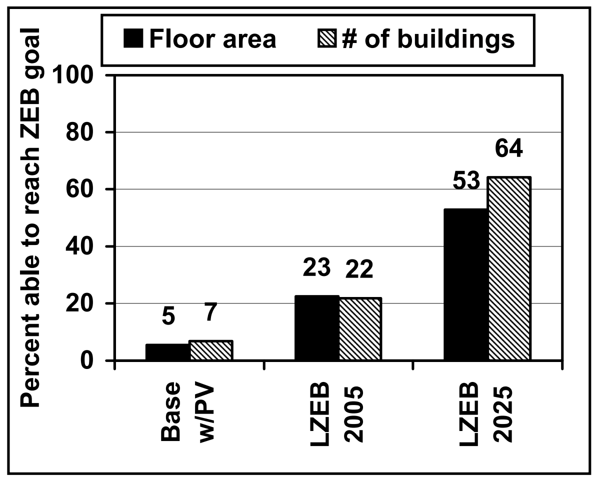

Figure 1 Percentage of the U.S. commercial sector that can reach the ZEB goal for various scenarios

We used Equation 1 to compare the three alternative scenarios to the base scenario and to determine the average level of energy savings. These results are presented in Figure 2 in terms of net savings (which include PV power systems) and total savings (which include only changes in efficiency).

The "LZEB 2005" scenario examined what can be achieved if an aggressive package of current technologies and practices to improve energy efficiency was also applied. This scenario showed that the amount of floor area that could reach ZEB reaches 23% and, for the sector as a whole, 69% of site energy could be saved in this manner.

Under the "LZEB 2025" scenario, we modeled two main performance differences—a doubling of the output available from rooftop PV panels and a 50% reduction in LPD. Under this scenario, 53% of the commercial floor area could achieve net zero and, for the sector as a whole, 105% of the site energy could be saved or 5% more energy could be produced than consumed by all the buildings in the sector.

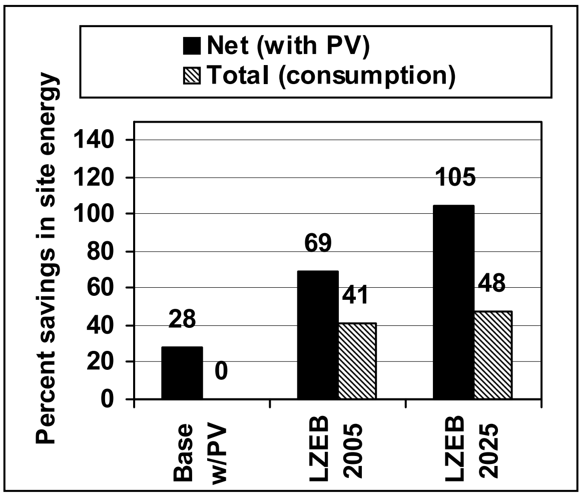

Figure 2 Percent savings in site energy for the U.S. commercial sector for various scenarios (100% represents ZEB)

Characteristics That Influence ZEB

The characteristics that influence the ability to reach the ZEB goal can be examined. For example, the sector model buildings can be binned by the number of floors or the total floor area and then reapplying Equation 2 to the resulting subsets of N. Figure 3 shows the percent of commercial floor area that can reach ZEB as a function of the number of floors. Figure 4 shows the percent of commercial floor area that can reach ZEB as a function of the total floor area of each building. Figures 3 and 4 are plots known as "XYSize," where the size of the plot symbols represents the probability distribution function of the individual bins versus the X-axis; the Y-axis represents the result for that bin. The results show that number of floors is a much stronger indicator of ability to reach ZEB than is overall size.

Although an N of 5,375 seems quite large, the sector model does not have enough members to hold up well when binned by more than one characteristic. For example, if the results were examined by number of floors and floor area at the same time, many bins would have too few members for the analysis to be statistically valid.

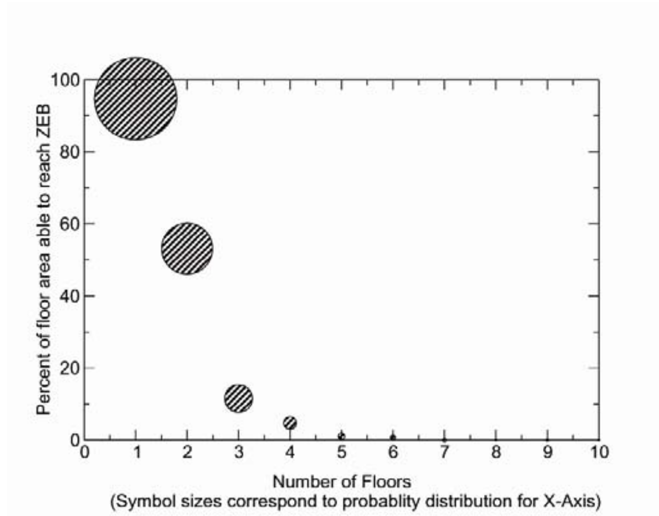

Figure 3 Percentage of floor area that can reach ZEB as a function of number of floors in building: LZEB 2025 Scenario

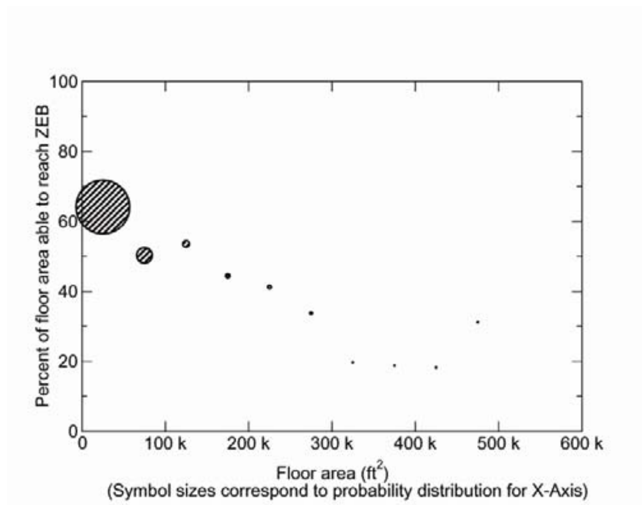

Figure 4 Percentage of floor area that can reach ZEB as a function of total floor area in building: LZEB 2025 Scenario

Limitations

The main disadvantage of this method is that the large number of models increases computing requirements, which precludes the evaluation of large numbers of scenarios with different technologies and practices. This points to a fundamental tension between modeling the national implications of technologies and practices and modeling a number of options for them. With current computing capabilities, for instance, the total number of simulations needs to be kept reasonably low (<100,000). The tension here can be somewhat alleviated with supercomputing and mass data storage resources, but the issue will persist because the number of models tends to grow geometrically and can easily swamp even the largest computing and storage capabilities. As a result, this methodology is recommended for future analyses when the results must properly reflect the national implications and when only a limited number of scenarios need be investigated. However, more efficient methods are needed with a relatively smaller set of buildings (<200) so researchers can investigate larger numbers of scenarios with different technologies and practices (parametric input perturbations).

The 2003 CBECS public use data should become available in 2006, and any future such modeling based on CBECS should use the new data set rather than the 1999 CBECS.

CONCLUSION

A methodology was presented, and is suggested as useful, for evaluating the whole-sector energy performance potentials for commercial buildings. The method consists of sector modeling and building modeling. Basing the sector model directly on CBECS provides a solid statistical basis that instills confidence that the results properly reflect the entire sector. Modeling the energy performance of individual buildings requires numerous details to be synthesized that are not available from the sector model. Generating the necessary detail is inexact and cumbersome, but it is possible.

The primary benefit of the method is that the CBECS weighting factors provide a robust way of aggregating national results from simulations of individual buildings. However, it is also challenging because it requires considerable computing resources. The methodology is recommended for future analyses when the results must properly reflect the national implications and when only a limited number of scenarios need to be investigated.

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