



U.S. DEPARTMENT OF
ENERGY

PNNL-18658

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

Analyzing the Life Cycle Energy Savings of DOE-Supported Buildings Technologies

KA Cort JA Dirks
DJ Hostick DB Elliott

August 2009



Pacific Northwest
NATIONAL LABORATORY

*Proudly Operated by **Battelle** Since 1965*

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor Battelle Memorial Institute, nor any of their employees, makes **any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights**. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or Battelle Memorial Institute. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

PACIFIC NORTHWEST NATIONAL LABORATORY

operated by

BATTELLE

for the

UNITED STATES DEPARTMENT OF ENERGY

under Contract DE-AC05-76RL01830

Printed in the United States of America

**Available to DOE and DOE contractors from the
Office of Scientific and Technical Information,
P.O. Box 62, Oak Ridge, TN 37831-0062;
ph: (865) 576-8401
fax: (865) 576-5728
email: reports@adonis.osti.gov**

**Available to the public from the National Technical Information Service,
U.S. Department of Commerce, 5285 Port Royal Rd., Springfield, VA 22161
ph: (800) 553-6847
fax: (703) 605-6900
email: orders@ntis.fedworld.gov
online ordering: <http://www.ntis.gov/ordering.htm>**



This document was printed on recycled paper.

(9/2003)

Analyzing the Life Cycle Energy Savings of DOE-Supported Buildings Technologies

KA Cort JA Dirks
DJ Hostick DB Elliott

August 2009

Prepared for
the U.S. Department of Energy
under Contract DE-AC05-76RL01830

Pacific Northwest National Laboratory
Richland, Washington 99352

Summary

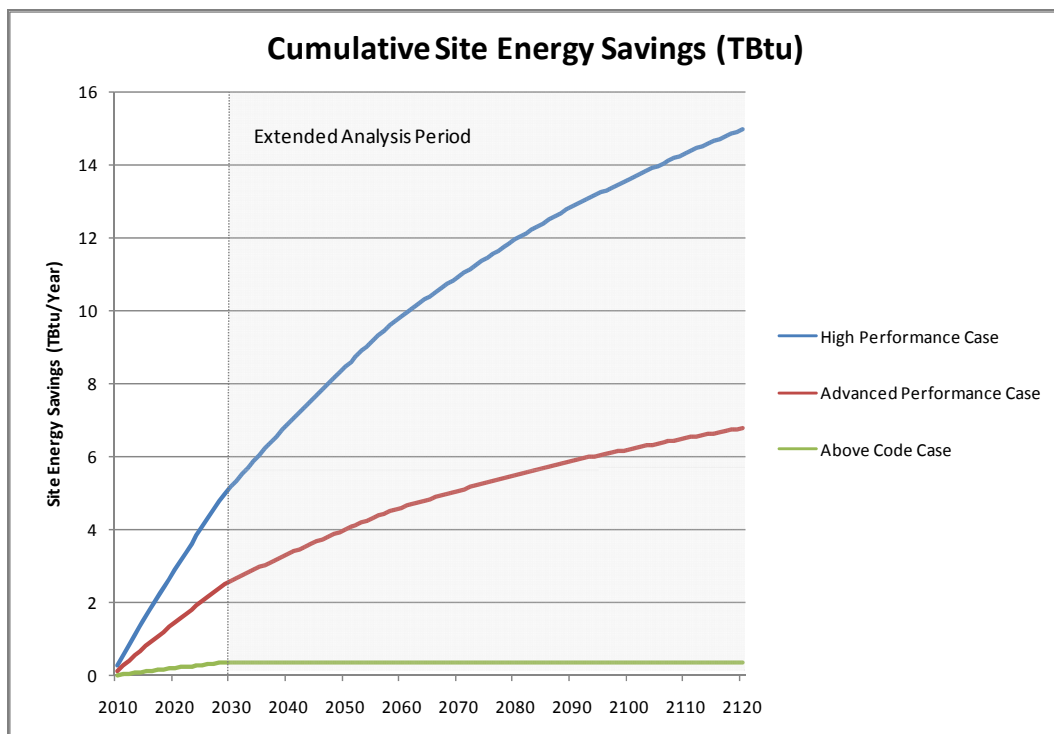
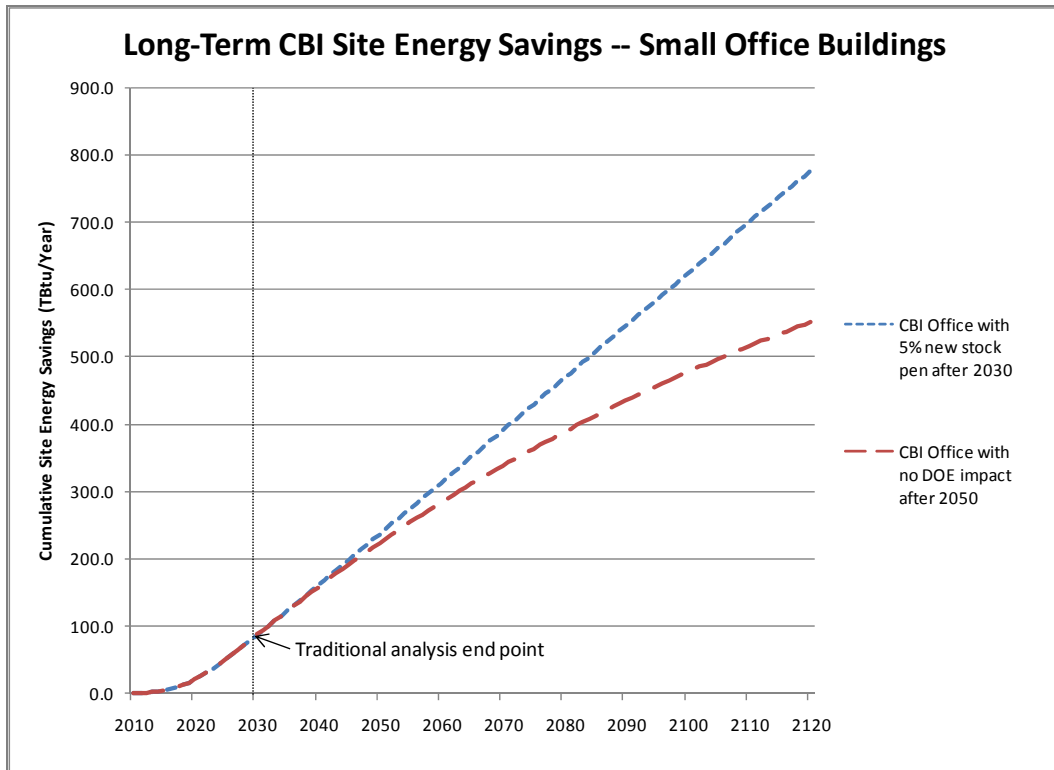
This report examines the factors that would potentially help determine an appropriate analytical timeframe for measuring the long-term benefits of government-funded research, development, and deployment. The Building Technologies Program (BTP) of the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) was examined. This program conducts long-term research and development (R&D), testing and evaluation, labeling and standards, and a host of implementation programs that directly impact the building marketplace.

To date, in accordance with guidance issued by the EERE Team within the Office of Planning, Analysis, and Evaluation (PAE), the projection of benefits for BTP has been constrained to the time horizon embedded in the "long-term" models maintained by PAE: the National Energy Modeling System (NEMS) and the MARKet ALlocation (MARKAL) model. NEMS is currently limited to the year 2030, while MARKAL extends the time horizon to 2050. Given the slow turnover in building stock and the extremely long lifetimes of buildings, combined with the longer-range goals of BTP, it is an open question as to whether these time horizons are sufficient to capture even a small part of the potential efforts to reduce energy use in the buildings sector.

This document presents a summary-level analysis of the life cycle savings for one segment of BTP's R&D portfolio: the Commercial Buildings Integration (CBI) R&D program (see "Long-Term CBI Site energy Savings – Small Office Buildings" figure below). The analysis addresses the question regarding whether the current time horizon (through 2030) disproportionately diminishes the impacts of buildings programs by prematurely truncating life cycle primary energy and carbon savings. To represent the long-range impacts of the CBI program, this analysis develops hypothetical building designs, which are in turn impacted by selected BTP R&D activities that are implemented through a sustainable building design rating system. The estimated energy use of these hypothetical building designs are projected over time for three hypothetical building cases (see "Cumulative Site Energy Savings" figure below), where assumptions are made regarding the timing and characteristics of major building retrofits that would potentially impact energy consumption of the selected buildings through the life of the building.

Pacific Northwest National Laboratory's Buildings Energy Analysis and Modeling System (BEAMS) was used to estimate the resulting energy and carbon savings associated with the hypothetical aging buildings impacted by the CBI R&D program. The analysis required extending the BEAMS modeling framework from a time horizon similar to NEMS and MARKAL to 110 years forward (the year 2120). These timeframes are similar to those now being considered for long-term modeling of potential climate change impacts.

The latter section of this report identifies the tasks required to develop a long-term analytical and modeling framework and discusses the potential analytical gains and losses by extending an analysis into the "very long-term." The baseline reference case developed for the traditional 20-year analysis of BTP benefits has relied heavily on established sources (e.g., Energy Information Administration data) and near-term extrapolations of simulated data. The extension of these data beyond 2030 required use of new data sources as well as an additional level of forecasting to extend the reference case out 110 years. Although we believe this extended analytical period more adequately captures the full long-term benefits, it also introduces an additional layer of complexity and uncertainty to the modeling framework for the years beyond the traditional 20-year time horizon. This report discusses and summarizes these issues and provides recommendations for future research in this area.



Acronyms and Abbreviations

AEDG	Advanced Energy Design Guide
AEO	Annual Energy Outlook
AIA	American Institute of Architects
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning
BEAMS	Building Energy Analysis and Modeling System
BREEAM	Building Research Establishment's Environmental Assessment Method
BTP	Buildings Technologies Program
Btu	British thermal unit(s)
CASBEE	Comprehensive Assessment System for Building Environmental Efficiency
CBI	Commercial Buildings Integration
CBECS	Commercial Buildings Energy Consumption Survey
CO ₂	carbon dioxide
DOE	U.S. Department of Energy
EERE	Office of Energy Efficiency and Renewable Energy
EIA	Energy Information Administration
ETSAP	Energy Technology Systems Analysis Programme
EUI	energy use intensity
ft ²	square foot (feet)
HVAC	heating, ventilation, and air conditioning
IES	Illuminating Engineering Society of North America
LBNL	Lawrence Berkeley National Laboratory
LEED	Leadership in Energy and Environmental Design
MARKAL	Market Allocation (model)
NBI	New Buildings Institute
NEMS	National Energy Modeling System
NRC	National Research Council
PAE	Office of Planning, Analysis, and Evaluation

PNNL	Pacific Northwest National Laboratory
R&D	research and development
RECS	Residential Energy Consumption Survey
TBtu	trillion British thermal units
USGBC	U.S. Green Building Council
ZEB	Zero Energy Buildings

Contents

1.0	Introduction	1
1.1	Purpose.....	2
1.2	Report Contents and Organization	2
2.0	Life Cycle of Building Energy Savings.....	2
2.1	The Case of High Performance Commercial Buildings.....	3
2.2	Savings Persistence: Following the Path to Market	8
2.2.1	Building Design Rating Systems.....	8
2.3	Building Characterizations for Three Cases.....	11
2.4	Energy Savings for the Three Cases.....	13
3.0	Challenges and Uncertainties of Long-Term Analysis.....	16
4.0	Conclusions and Recommendations	18
5.0	References	18

Figures

1	Key Design Features of the Highest Performing Buildings Likely to Result in Long-Term Persistent Savings	5
2	Design Features of High Performance Office Building – Taken from Aldo Leopold Legacy Center in Bariboo, Wisconsin.....	6
3	Cumulative Potential Savings of CBI Assuming Long-Term Savings Persistence of Impacted Building Stock	7
4	Cumulative CO ₂ Emissions Reductions Potential of Commercial R&D Program	8
5	Likely Energy-Related Retrofits During Life of Commercial Office Building	14
6	Savings Measured Over Time for Sample Office Building.....	15

Tables

1	Energy Performance Characteristics for Three Cases.....	13
---	---	----

1.0 Introduction

Each year, the U.S. Department of Energy's (DOE's) Office of Energy Efficiency and Renewable Energy (EERE) estimates the potential energy and carbon impacts of program activities as proposed in the President's budget submitted to Congress. EERE's Team, within the Office of Planning, Analysis, and Evaluation (PAE) issues guidance and collects information required to exercise an integrated modeling suite to produce estimates of the energy security, environmental, and economic impacts expected from EERE's budget request. These expected benefits (i.e., impacts of the programs) are reported in the DOE Congressional Budget Request and include the following measures:

- Energy Security
 - oil imports reduction
 - natural gas imports reduction
 - reduction in share of highway fuel demand derived from crude oil
- Environmental Impacts
 - carbon dioxide (CO₂) emissions reduction
 - sulfur dioxide allowance price reduction
 - nitrogen oxides allowance price reduction
 - mercury allowance price reduction
- Economic Impacts
 - consumer savings
 - electric power industry savings
 - household energy expenditures reduction.

PAE only develops and publishes benefits estimates at the program level, meaning that “official” estimates are only available for the Buildings Technologies Program (BTP) as a whole.¹ To conduct program planning, BTP has funded Pacific Northwest National Laboratory (PNNL)² to provide a much more detailed set of benefits estimates by individual budget line item for all activities (e.g., Commercial Buildings Integration, Solid-State Lighting) and even for competing and complementary activities within a budget line item.

PNNL has developed an internal tool, the Building Energy Analysis and Modeling System (BEAMS), to calculate the benefits associated with the various buildings activities. BEAMS is a bottom-up accounting model that compares estimated baseline building energy use against the estimated building energy use of buildings with specified technologies and envelope features (Elliott et al. 2004). In addition to energy savings forecasts, these results also include such items as associated environmental emissions, consumer energy cost savings, and necessary capital investments.

Traditionally, PNNL's impact analysis performed for BTP has been tied to the Office-wide impact analysis for EERE's annual budget submissions. Because EERE uses a modified version of DOE's

¹ A more detailed description of the process and models used by EERE can be found in the most recent documentation, available at <http://www1.eere.energy.gov/ba/pba/pdfs/41347.pdf>.

² PNNL is operated by Battelle for the U.S. Department of Energy under Contract DE-AC05-76RL01830.

National Energy Modeling System (NEMS)¹ model to project program impacts, PNNL has drawn most of the reference case assumptions from the NEMS model and outputs, which currently extends to 2030. EERE has attempted to extend the analysis period through 2050 using a modified version of the MARKet ALlocation (MARKAL)² model.

1.1 Purpose

PNNL currently develops impact estimates for BTP activities out to the year 2030. Within the buildings sector, many energy efficiency improvements (stemming from DOE research and development [R&D] investments) can be expected to last the life time of the building if maintained and operated properly (although some degradation may occur). As interest increases in the longer-term impacts of EERE activities, particularly with regard to carbon emissions reductions, the ability to extend the analysis period becomes more desirable. PNNL therefore undertook an effort to extend the analysis period within the BEAMS framework allowing an analysis of the benefits throughout the building life time.

1.2 Report Contents and Organization

This report identifies the factors that would determine an appropriate analytical timeframe for measuring building energy impacts. The analysis presents a summary-level life cycle assessment of building energy savings, using the technologies, designs, and research supported by BTP's Commercial Buildings Integration (CBI) R&D activity. To build the framework for extending the BEAMS model timeframe, three hypothetical commercial building designs are characterized within the model. Preliminary primary energy savings results are estimated over a 110-year timeframe to illustrate the resulting energy and carbon savings associated with this building stock as it ages over time. The 100-year timeframe is typical for current models that consider potential long-term climate impacts.

In the latter section of this report we identify the tasks required to develop a long-term analytical framework. We also discuss the potential analytical gains and losses by extending an analysis into the "very long-term." Finally, we provide recommendations for future research in this area.

2.0 Life Cycle of Building Energy Savings

The savings that result from reducing energy usage in long-lived capital assets such as buildings are realized over time. But precisely what time horizon is appropriate is to consider is another question: is it 30 years? 60? 100? The full life cycle savings depend not simply on the useful life of the asset, but also how the savings persist over time, which is a function of the characteristics of the energy saving program, the technologies or designs used, and the operation and life of the structures that house these technologies and designs. To understand the life cycle benefits of a building energy design or technology, we must understand the life cycle of a building.

¹ NEMS is an integrated energy model of the U.S. energy system that was developed by DOE's Energy Information Administration (EIA) for forecasting and policy analysis purposes.

² MARKAL is an integrated energy systems optimization model that was developed by the Energy Technology Systems Analysis Programme (ETSAP) of the International Energy Agency.

For energy modeling purposes, the EIA estimates the median value for the lifetime of commercial buildings, based on analysis of data from Commercial Buildings Energy Consumption Survey (CBECS). The median lifetime values range from 65 to 80 years, depending on the type of building (EIA 2009). The actual life of a given building will typically depend on a number of factors, including the type of building (e.g., retail, office, single-family), physical characteristics of building materials, exposure to the elements, maintenance regime, and frequency of use. In addition, the behavior of building owners will play a role in determining the life of a building.

Although some building energy-saving designs and technologies could potentially produce continuous savings throughout the lifetime of a building, others will not. Even energy-saving approaches integral to the design of the building may not save energy over the full building lifetime due to retrofits or changes in building use. Thus, the life cycle of building energy savings will vary depending on the characteristics of the energy-saving components in combination with the characteristics of the building.

The approach PNNL currently uses to calculate energy impacts specifically considers “the lifetime” of a given technology. Therefore, when considering BTP activities that focus on specific building technologies such as solid-state lighting, we factor in the potential lifetime of the product when estimating the potential savings. For “whole building” or integrated design (building shell) activities that impact overall building energy consumption (as opposed to equipment or other building components), “the lifetime” of the savings is currently assumed to extend the length of the analysis period. That is, no explicit consideration of the lifetimes of “long-term” technologies is required when the timeframe “only” extends to 2030. To explore the “very long-term” savings of activities targeting the building shell and/or whole building energy use, this analysis examines the energy savings approach of BTP’s CBI R&D, which focuses on whole building energy savings.

We have chosen to look at the measures potentially specified by popular building rating systems to provide a mechanism for assessment of the specific building characteristics and the corresponding impacts that extend beyond any artificial planning horizon, up to and including the life of the building stock. We began this analysis with the hypothesis that if the impacts of energy efficiency-related measures available for scoring under a building rating system were analyzed across the building lifetime or some similarly extended period beyond the 2030 planning horizon, the results might indicate that higher weighting should be applied to those elements of the rating system, compared to other measures not affected by measure duration. To assess the saving persistence potential of energy-related design features in buildings, we assess the guidance and scoring features of some rating design systems and describe a potential pathway that the CBI activities might follow from R&D to the building marketplace. Next, we characterize three hypothetical office buildings cases with a range of building energy savings measures, and then track the potential savings for the three buildings over time.

2.1 The Case of High Performance Commercial Buildings

BTP’s CBI program uses a systems-integration approach to enhance the technical energy efficiency of commercial buildings. CBI supports research, development, and demonstration of whole building design methods and operational practices that reduce energy usage. One example is the Advanced Energy

Design Guides (AEDGs),¹ which provide guidance for reducing energy costs by 30% to 50% relative to standard energy code-compliant building designs. Another example is decision tools tailored to high performance (i.e., highly energy-efficient) and Zero Energy Buildings (ZEB). These tools, designs, and technical information find their way into the building market in a number of ways, including deployment programs and partnerships directly supported by CBI and BTP. Additionally, a number of building design energy and sustainability rating systems serve as informal deployment instruments by facilitating promotion of energy-efficient advanced designs and technologies in the commercial building sector. “Sustainable” building designs could generally be defined as designs that are based on the principles of resource efficiency, health, and productivity, where a realization of these principles involves an integrated, multidisciplinary approach—one in which a building project considers a building’s total economic and environmental impact and performance, from material extraction and product manufacture to product transportation building design and construction, operations and maintenance, and building reuse or disposal (U.S. Green Building Council [USGBC] 1996). Some of the more prevalent design and rating systems employed in the U.S. commercial building market are discussed later in this report and are summarized in Appendix A.

The CBI integrated approach to designing high-performing buildings is not a prescriptive approach, and it does not necessarily endorse specific technologies or designs for all buildings; however, the general approach advocated by the AEDGs involves the integration of some basic steps and goals as part of the design process to ensure energy optimization for a given building. These basic steps include the following:

1. Reduce building energy loads (both internal and external): reduce heating gains/losses by building a well-designed, insulated building envelope. Reduce cooling loads by using an efficient electric lighting system and maximizing benefits of daylighting with good design.
2. Match the capacity of energy-using systems to the reduced loads: “right-size” the equipment. Oversized systems often cost more to purchase and install and will likely not operate at their optimum efficiency when they are mismatched to the load.
3. Design and install higher efficiency equipment: use less energy to meet any given load with the use of economizers and demand-controlled ventilation, more efficient interior and exterior lighting, and sensor and control strategies that reduce energy use. In systems whose capacity matches peak loads, high-efficiency equipment serving a building designed and constructed to the lowest practical loads will result in the lowest energy use and cost.
4. Integrate building systems to increase energy savings potential: integration of the design process helps to identify energy-efficiency opportunities, such as daylighting and appropriate zoning to help reduce internal loads. Using computer simulations of building energy use throughout the design process assists in finding the most energy-efficient designs.

¹ Current Advanced Energy Design Guides (AEDGs) available on the American Society of Heating, Refrigerating, and Air-Conditioning (ASHRAE) website for Small Retail, Warehouse, Office, and School Buildings at <http://www.ashrae.org/publications/page/1604>. Planned guides can be found at <http://www.ashrae.org/technology/page/938>. The guides have been developed as a collaborative effort by the following partnering organizations: the ASHRAE, the American Institute of Architects (AIA), the Illuminating Engineering Society of North America (IES), the USGBC, and DOE.

By its nature, a well-designed high-performance building will have all building energy components fully integrated. As such, it is difficult to attribute energy savings to any single building element. However, two sets of features would most likely result in long-term persistent energy savings throughout the life of the building (Figure 1). These include daylighting optimization design features and advanced heating, ventilation, and air-conditioning (HVAC) building systems in combination with a well designed, insulated building shell.

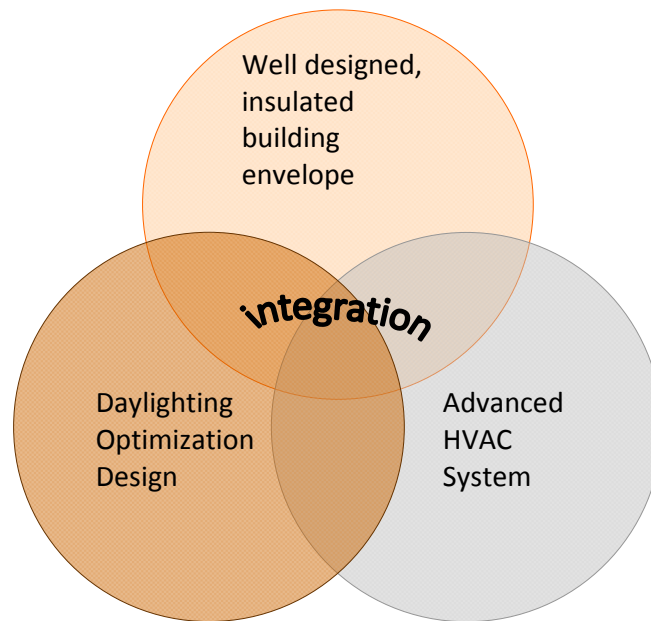


Figure 1. Key Design Features of the Highest Performing Buildings Likely to Result in Long-Term Persistent Savings

Daylighting optimizes the admission of natural light into a space through windows or skylights to reduce or eliminate the need for electric lighting. Natural lighting can also avoid glare and reduce the heat caused by electric lighting (Figure 2). More glazing (windows) does not automatically result in more or better daylighting. To maximize the benefit of natural light, it has to be controlled and distributed properly throughout the workspace. However, the design process is complex because it must carefully balance heat gain and loss, glare control, and variations in daylight availability. For example, successful daylighting designs will invariably pay close attention to the use of shading devices to reduce glare and excess contrast in the workspace. Additionally, window size and spacing, glass selection, the reflectance of interior finishes, and the location of any interior partitions must all be evaluated (Ander 2008).



Above – The construction of underground earth tubes (supplying tempered ventilation air to the facility) is part of an Advanced Building System, which includes a ground-source heat pump.

Below – Daylighting is optimized with a narrow footprint, oriented along an east-west axis, and integrated with buildings HVAC and lighting systems.



Figure 2. Design Features of A High Performance Office Building (Taken from Aldo Leopold Legacy Center in Baraboo, Wisconsin [Photo credit: The Kubala Washatko Architects, Inc.]

A number of advanced HVAC and mechanical system designs have proven energy-saving benefits in commercial buildings. One energy-efficient option is to simply use the most efficient conventional HVAC unit available. However, additional savings can be realized with more optimized system designs (i.e., “advanced systems”) that consider the interactions between the building, building systems, and the local climate and that take full advantage of efficient components, sensors, and controls. The Aldo Leopold Legacy Center in Baraboo, Wisconsin provides an example of an advanced building system design in a high performance building (Figure 2). The design approach was to reduce the load on the mechanical systems through optimal building design, and then install correctly sized, most highly efficient equipment on the market. Design measures included separating the ventilation system from the heating and cooling system and the use of buried earth tubes on the site, which allow preheating of ventilation air during winter and pre-cooling during summer before the air enters the building. Another measure was to create a “thermal flux zone” that reduces heat flow between the main office and the outdoors. A third measure was a highly efficient building envelope that reduces thermal transfer (loss of heat or cold) to the environment. Finally, a series of ground-source heat pumps connected to a radiant slab provide heating and cooling for the building.

While doubling and tripling insulation levels (above code) will result in incremental energy savings, the full benefit of a high performance building is not realized until daylighting (to reduce heating, cooling, and lighting loads) and advanced HVAC designs are implemented. When such designs are used, energy cost savings can increase to 50% or more.¹ Because these high performance design features are integral to the building design and not easily “changed out,” they are also the most likely to persist over the long term, potentially saving energy for the entire life of the building.

The CBI program goal is to reduce purchased energy use in new commercial buildings by 50% as compared with ASHRAE Standard 90.1-2004 in the near term, increasing to 70% savings by 2025 (EERE 2008). As presently modeled in BEAMS, the CBI program activities result in energy savings in heating,

¹ Design details for advanced performance buildings can be found in the current AEDGs available on the ASHRAE website for Small Retail, Warehouse, Office, and School Buildings at <http://www.ashrae.org/publications/page/1604>. A list of planned guides can be found at <http://www.ashrae.org/technology/page/938>.

cooling, water heating, and lighting. Currently, the savings are measured through 2030. When analyzing the impact of the CBI program, the current assumption is that CBI accelerates the adoption of advanced designs and technologies by approximately 8 years.¹ That is, without this government-supported R&D program, the adoption of these advanced designs and technologies is assumed to occur just 8 years later.

The percentage of commercial floor space impacted by this program is estimated using market penetration curves.² Figure 3 shows a simple example of the very long-term benefits of this program. If the savings were to persist at a sustained level for the entire life of the building, and if these buildings lasted for up to 110 years, the long-term savings would increase over time. Figure 4 shows the preliminary results of extending benefit estimates into the long term and illustrates the potential magnitude of cumulative energy savings of this program out to the year 2120 under two separate scenarios. The first scenario (blue dotted line) attributes a continuing new stock penetration of 5% per year to the CBI program after 2030. The second scenario (red dashed line) assumes no further impact of the DOE activity after 2050. Such an assumption might reflect the potential for the market to offer equivalent design practices without intervention by DOE. In either case, the “very long-run” savings under these two extended scenarios dwarf the results projected in 2030 and before.

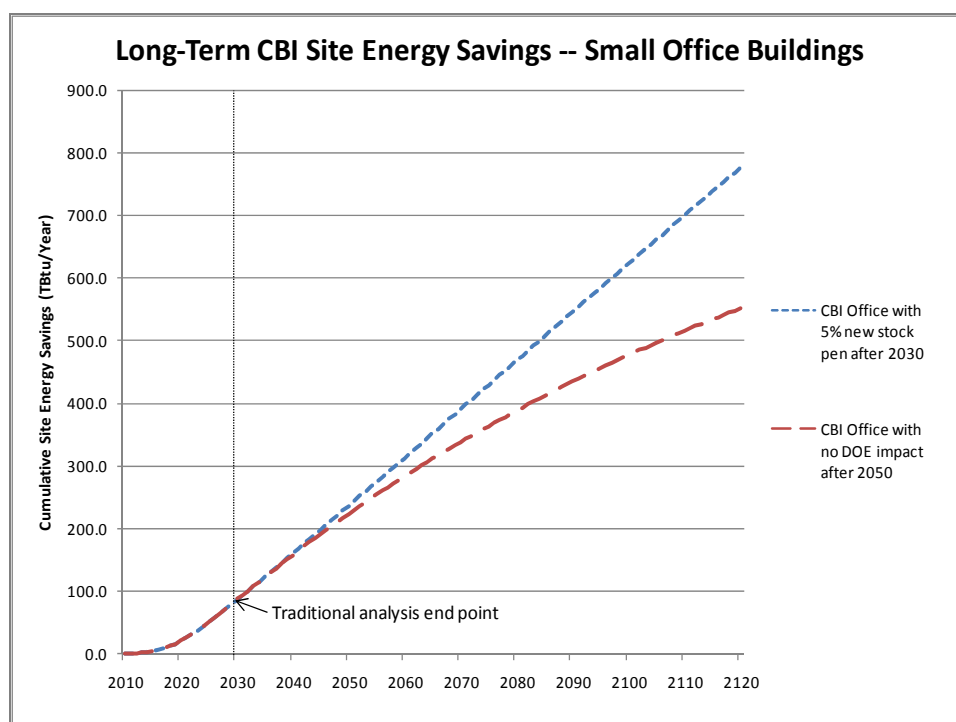


Figure 3. Cumulative Potential Savings of CBI (New Small Office Building) Assuming Long-Term Savings Persistence of Impacted Building Stock

¹ This assumption is broadly based on recommendations provided in a National Research Council report (NRC 2001) and adjusted for specific energy savings and payback features within the commercial buildings sector.

² The penetration rate forecasts used in this analysis were developed using diffusion curves as documented by Elliott et al. 2004. These diffusion curves describe a rate and path of market penetration over time from initial level to the eventual maximum.

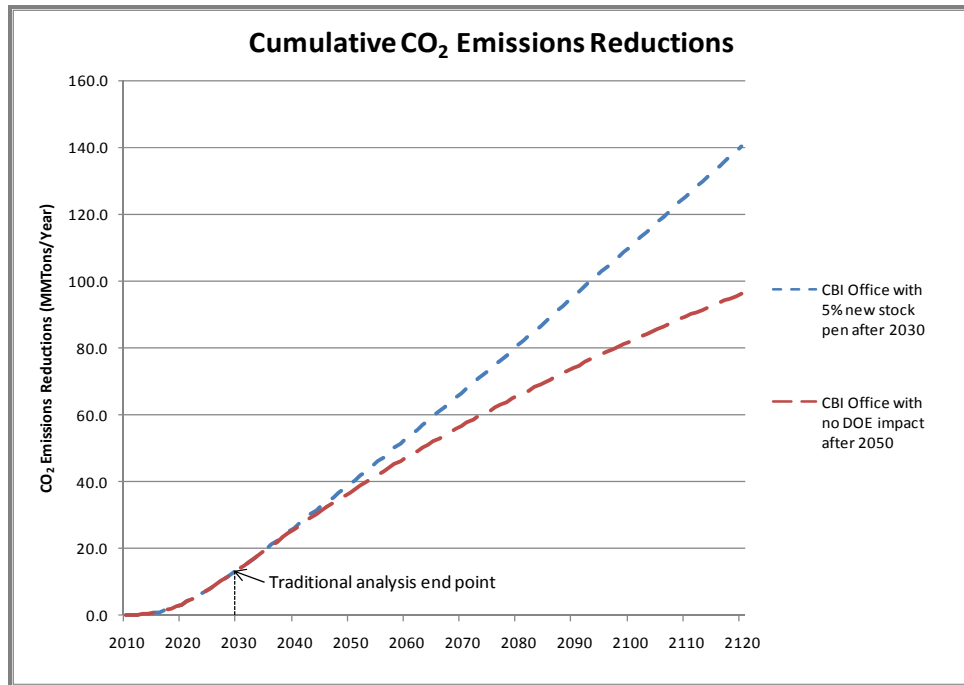


Figure 4. Cumulative CO₂ Emissions Reductions Potential of Commercial R&D Program (New Small Office Building)

2.2 Savings Persistence: Following the Path to Market

Given the slow stock turnover in buildings and the long-range nature of the CBI goal, it is evident that a 2030 cut-off vastly understates the potential impact of this program. However, is it reasonable to assume that the savings of each impacted building would persist at this level over the long term? To address this question, this analysis first attempts to identify potential pathways for these design approaches to enter the market to determine whether it is reasonable to assume that the longer lasting design elements and technologies actually penetrate the commercial building market. Next, we develop hypothetical building cases based on this information and estimate the savings over time.

In recent years, one of the more common ways that CBI tools, designs, and information find their way into the building market is through sustainable building design rating systems. In the past decade, the popularity of these building design rating systems has grown such that they have become deployment instruments for advanced building design research, promoting various advanced designs and technologies in the commercial building sector. Most of these rating systems include energy efficiency as a fundamental part of their criteria. To follow a possible path from design concept to actual building design, this report examines an assortment of building design rating systems.

2.2.1 Building Design Rating Systems

Numerous building rating systems include ratings and evaluations of building energy use (either simulated or metered) and/or energy efficiency measures. A 2006 PNNL study completed for the U.S. General Services Administration reviewed 30 sustainable building rating systems and identified five

design rating systems¹ that focus on a whole building evaluation (rather than individual design features), provide clear ways to evaluate designs, and are applicable to most all commercial buildings in the U.S. market (Fowler and Rauch 2006). Considering their whole building approach, these sustainable design rating systems would appear to align well with CBI's focus on whole building integrated energy design. It should be noted, however, that all five of the rating systems focus on sustainability, rather than exclusively on energy efficiency.

Although the criteria are not exclusively focused on energy efficiency, sustainable design rating systems include criteria that specifically address optimizing energy usage in the building design. Of the five rating systems reviewed by Fowler and Rauch, approximately 20% to 35% of all the points earned as part of the rating systems are directly linked with energy system design optimization. In addition, energy efficiency and projected energy consumption are often indirectly impacted by other rating categories such as water conservation, site optimization, and operational and maintenance practices. All rating systems reviewed focus on reducing overall building energy consumption through energy demand minimization measures, energy-efficient systems and "right sizing" of equipment, and all include credit for various renewable² sources of energy (Fowler and Rauch 2006).

Of the five rating systems reviewed, LEED is currently the dominant system in the U.S. market and is being used in 91 other countries (Fowler and Rauch 2006). LEED was developed and piloted in the United States in 1998 by USGBC member committees as a consensus-based building rating system and an ecology-oriented building certification program.³ The LEED rating system addresses specific environmental building-related impacts using a whole building environmental performance approach, where points are earned as part of six different categories: sustainable sites, water efficiency, energy and atmosphere, materials and resources, indoor environmental quality, and innovation. USGBC has rating systems for new construction and major renovations, existing buildings, and other special design circumstances and building types. The most commonly used LEED rating system is for new construction and major renovation, which is the reference system for this analysis. Approximately 25% of the LEED (Version 2.2)⁴ points that can be earned are directly related to energy optimization (USGBC 2005). In addition, all LEED-certified buildings are required to meet a minimum expectation of modeled energy use that is 14% better than a building built at the ASHRAE Standard 90.1-2004 level. Building energy commissioning⁵ is mandatory for LEED-certified buildings, and additional credits are available for

¹ The five systems included: Building Research Establishment's Environmental Assessment Method (BREEAM), Comprehensive Assessment System for Building Environmental Efficiency (CASBEE), GBTool, Green GlobesTM U.S., and Leadership in Energy and Environmental Design (LEED). For more information on each building rating system, see Appendix A.

² Although Zero Energy Building (ZEB) designs (i.e., buildings designs where the building produces as much energy on site as it consumes on an annual basis) supported by CBI would include some portion of on-site renewable energy, this analysis focuses on the high-performance energy-efficiency aspects of the building and does not include renewable energy.

³ More information on the history and statistics about LEED rating system is found on USGBC website <http://www.usgbc.org/> and in the Green Building fact sheet (including updates of statistics) found at <http://www.usgbc.org/DisplayPage.aspx?CMSPageID=1718>.

⁴ For this analysis, specifics related to LEED's rating and point system are based on LEED-NC Version 2.2, published in October 2005. A newer version of LEED (Version 3.0) published in June 2009 is available at the following site: <http://www.usgbc.org/DisplayPage.aspx?CMSPageID=1970>.

⁵ Building commissioning is the process of ensuring that all the subsystems for HVAC, plumbing, electrical, fire/life safety, and building security in new construction are operating as intended by the building owner and as designed by the building architects and engineers.

daylighting strategies. LEED requires the design team to use energy modeling to document the designed energy performance or to follow and document the prescriptive path outlined in CBI's AEDGs (when available for the given building type).

The LEED rating system's growing impact on the commercial buildings market can be represented by the number of projects registered, up from 93 projects in 2001 to a total of over 18,000 registered projects as of March 2009.¹ Several cities now require LEED certification for large commercial projects, and many states are requiring LEED for public buildings (Brook 2008). Thus, the LEED rating system potentially provides opportunities to deploy many of the design strategies currently supported by CBI.

The question remaining, however, is whether these longer lasting (but potentially more costly) design features such as advanced HVAC designs and daylighting are incorporated into building designs that attempt to achieve certification as part of a LEED rating process. In addition, is the resulting energy usage of these LEED-certified buildings at a level that indicates these design features are implemented and actually saving energy relative to standard practice?

Some have criticized the LEED point system for not providing appropriate weighting based on the life cycle of the environmental benefit associated with energy efficiency design elements. The extreme case cited in a 2004 survey of architects² occurred when one building owner received one point for spending "an extra \$1.3 million for a heat-recovery system that will save about \$500,000 in energy costs per year" and also received one point for installing "a \$395 bicycle rack." Some have argued that this type of weighting leads to point-mongering, where builders will look for the cheapest and easiest points to implement and disregard some of potentially higher-cost environmental features that offer sustaining benefits, such as advanced building energy systems. It should be noted that USGBC has since revised its LEED credits and, although it still uses the checklist, the revised point system disqualifies any building that does not score at least two points for energy efficiency, equivalent to 14% better than the energy standard code. The LEED Version 3.0 (published in June 2009) is weighted to give even more importance to features that reduce global warming and the ability to acquire energy-efficiency points will be nearly doubled (Brook 2008).

To specifically address whether the longer-lasting energy-efficient features are being included in the LEED-certified buildings, this analysis first explores the simple question of whether LEED-certified buildings are using less energy than the commercial building stock. In a recent study commissioned by USGBC, the New Buildings Institute (NBI) examined the energy performance of 121 new commercial LEED-certified buildings. The results demonstrated that LEED buildings improved energy performance over the general commercial building stock reported in the CBECS. The energy use intensity (EUI) of LEED office buildings was estimated to be approximately 33% lower than CBECS offices. The study also showed that overall LEED-certified building EUIs, regardless of building type, were 24% lower than CBECS buildings. These levels of savings would imply that LEED buildings are incorporating at least some of the more design-intensive energy-saving features. It was also observed, however, that a number of buildings in the study were not performing to their design potential (Turner and Frankel 2008). This result is not necessarily surprising, considering that a number of studies have called attention to the frequent disparity between performance design and actual performance, particularly for higher

¹ USGBC. 2009. Green Building Facts. URL: <http://www.usgbc.org/ShowFile.aspx?DocumentID=3340> (accessed on March 9, 2009).

² Conducted by the Green Building Alliance, a Pittsburgh-based coalition of environmental groups.

performance buildings (see article insert on building performance commissioning). In an effort to close the design-to-actual performance gap, LEED requires that all buildings be commissioned upon completion and before certification, and repeat commissioning throughout the life of the building can earn the building an additional point toward the “energy optimization” category.

Another Plug for Building Energy Performance Commissioning . . .

When it comes to assessing the long-term impacts of high performance buildings, the 800-pound gorilla in the room has been and remains the gap between the design performance and actual performance of a building. As summarized by Ryan and Nicholls in their 2004 American Council for an Energy-Efficient Economy paper on Commercial Buildings R&D, this gap may be even larger for high performance energy-efficient building designs that use an integrated building system approach because these considerably more complex designs present greater performance challenges. More complexity increases the probability of errors in design and execution, and hence an increased probability of greater divergence between design intent and actual building performance.

Numerous studies have documented the disparity between design and actual performance. In a study directly focusing on high performance buildings (Torcellini et al. 2004), all six buildings examined performed below their design goals. Performance issues included inaccurately stipulated insulation levels, installation of incorrect window frames, thermal short-circuits in building envelope, deficient lighting control calibration and algorithms, malfunctioning ventilation controls, poorly located exhaust dampers, and temperature setbacks out of compliance with design intent. While commissioning would not have entirely closed the gap between expected and actual performance for these buildings, it would have made a contribution towards doing so. Even when buildings are operated as designed, sustaining that optimal performance over time becomes an added challenge for buildings with complex systems. In a 2004 meta-analysis performed by Lawrence Berkeley National Laboratory (LBNL), 3305 energy system deficiencies were identified out of 34 building projects reviewed, with HVAC systems appearing to present most of the problems, particularly within air-distribution systems (Mills et al. 2004). These general findings were recently confirmed in an updated and expanded LBNL commissioning case study that analyzed 643 buildings in 26 states (Mills 2009). Additional commissioning, or recommissioning throughout the life of a building could assist in reducing the design-to-actual performance gap.

To address the question of whether the more design-intensive, longer-lasting energy-optimizing designs are being incorporated into LEED buildings, the design features and scores of 20 LEED-certified office buildings were reviewed, drawn from the DOE’s High Performance Buildings Database.¹ In the 20-building sample examined, all 20 office buildings included documentation of advanced designs elements that would potentially save 30% of energy costs relative to the benchmark (which was ASHRAE Standard 90.1-1999 for some of the older buildings and 90.1-2004 for the more recently constructed buildings). Information from the High Performance Buildings Database indicated that all 20 office buildings that were examined included at least some daylighting optimizing features as part of their

¹ The 20 buildings represented all commercial office projects (sized between 1000 and 50,000 square feet [ft²]) maintained in the DOE-sponsored High-Performance Buildings Database. This database represents a collection high-performance buildings data including factors that affect a building's performance, such as energy design, materials, and land use. This searchable database is currently available at the following weblink: <http://eere.buildinggreen.com> (accessed on February 22, 2009)

designs. It would appear that a smaller number of buildings documented advanced HVAC strategies such as ground-source heat pumps; however, the database does not necessarily include a comprehensive list of all features, so it is difficult to say with certainty whether these features were not a part of the building design. For approximately 40% of the office buildings reviewed, their designs were documented as having maximized energy reduction opportunities (energy cost reductions of about 60% over benchmark) by taking advantage of both daylighting opportunities and using advanced mechanical and/or HVAC design elements such as ground-source heat pumps, under-floor air-distribution systems, and thermal heat chimneys. In general, incorporation of at least some of the more design-intensive energy-optimizing features appears to be standard practice for LEED-certified buildings.

2.3 Building Characterizations for Three Cases

To assess the potential impacts of high performance buildings over time, we developed three sets of building characteristics, based on typical features found in the High Performance Buildings Database. The three cases are characterized as follows:

- a “High Performance Case,” representing a hypothetical highly rated building that incorporates both advanced equipment choices as well as advanced design (reducing the building load by approximately 50% relative to standard building practices and/or code ASHRAE Standard 90.1-2004),
- a medium performance building, which we will refer to as the “Advanced Performance Case,” representing a hypothetical rated building that incorporates high-efficiency equipment as well as some advanced design elements to reduce lighting loads and maximize use of daylighting in the building (reducing the building load by approximately 25%), and
- an “Above Code Case,” representing a building that incorporates some advanced technologies but no changes to current design (reducing the building load by approximately 5%).

The hypothetical High Performance Case building is characterized as a small (under 50,000 ft²) commercial office building that is designed to use on average approximately 50% less energy than a similar office building built just to the ASHRAE Standard 90.1-2004 level. It is assumed that this building would be located in a heat-load-dominated climate. In terms of building rating systems, this building would be equivalent to a LEED-certified building that achieves all 10 of the “energy optimization” points available as part of rating system and would likely receive an additional point for innovation (USGBC 2005).

The High Performance Case characterized the office building as having a highly insulated building envelope to reduce heat transfer. The use of structural insulated panels in place of frame construction increases the thermal resistance value of the walls. Water-to-water ground-source heat pumps are used to heat and cool the building. An earth-tube system provides fresh, tempered air in all seasons and the air-handling unit delivers only the required ventilation air, such that the fan size can be reduced compared with typical systems. Displacement ventilation, variable-frequency-drive fans, and demand-controlled ventilation are also used to reduce energy demand. The office building is designed to maximize daylighting benefits and thus reduce heating, cooling, and lighting loads by orienting the building along an east-west axis with building overhangs to shield sun in the summer and allow passive heat gain in the winter. Sensors and controls are installed to optimize daylighting benefits in coordination with the lighting system. Lighting technology is made up of T8 linear fluorescent lighting and compact fluorescent task lighting.

Table 1. Energy Performance Characteristics for Three Cases (northern small office buildings)

	High Performance Case (50% energy use reduction)	Advanced Performance Case (25% energy use reduction)	Above Code Case
Building Shell/Envelope			
Roof insulation	R-Value = 30	R-Value = 30	R-Value = 15
Wall insulation	R-Value = 27 (structural insulated panels)	R-Value = 16	R-Value = 13
Floor insulation	R-Value = 13 (perimeter)/ R-Value = 10 (slab)	R-Value = 13 (perimeter)/ R-Value = 10 (slab)	R-Value = 8
Windows	U-Value = .35 Shading Coefficient = .365	U-Value = .35 Shading Coefficient = .365	U-Value = .57 Shading Coefficient = .39
Building Systems			
Equipment and Design	Ground-source water-to-water heat pump with radiant slabs for space heating and cooling. Earth-tube system provides fresh, tempered air with demand-controlled ventilation. Intermittent use zoned separately, thermal flux zones between different uses.	High-efficiency packaged unit for heating and cooling. Demand-controlled ventilation.	High-efficiency packaged unit for heating and cooling.
Lighting			
Equipment	T8 fluorescent, electronic ballasts (some dimmable), task lighting, sensors, and controls	T8 fluorescent, electronic ballasts (some dimmable), task lighting, sensors, and controls	T8 fluorescent, electronic ballasts
Daylighting	Building and lighting controls designed to maximize daylighting	Building and lighting controls designed to maximize daylighting	No specific daylighting features
Other			
Exterior design	Orientation designed to maximize conditioning and daylighting impacts. Reflecting roofing and landscaping designed to reduce heat island effect. Engineered overhangs.	Orientation designed to maximize conditioning and daylighting impacts. Reflecting roofing and landscaping designed to reduce heat island effect.	No particular energy-efficient features
Building Commissioning	Commissioned on repeat basis	Commissioned on repeat basis	Building commissioned upon completion
Indoor Equipment	Efficient appliances assumed	Efficient appliances assumed	Efficient appliances assumed

The Advanced Performance Case building is characterized with many characteristics similar to the High Performance Case in that daylighting design is optimized, and sensors and controls are used to maximize daylighting benefits. The building envelope is also characterized as exceeding code with twice the R-Value for roof insulation of the ASHRAE Standard 90.1-2004 for a heat-load dominated region of

the country; however, the walls have a lower R-Value than the High Performance Case. The primary difference between the High and the Advanced Performance Case buildings is that the Advanced Performance Case does not include any advanced mechanical building systems, such as the ground-source heat pump included in the High Performance Case. In terms of building rating systems, the Advanced Performance Case would be equivalent to a LEED-certified building that achieves approximately half (5 out of 10) of the “energy optimization” points or at least 24.5% better than energy ASHRAE Standard 90.-2004 level (USGBC 2005).

The Above Code Case building is characterized as just meeting code for all building envelope requirements. Although the Above Code Case uses the same basic lighting technology (T8 linear fluorescent lighting with electronic ballasts) as the High Performance and Advanced Performance cases, it does not have any specific daylighting design features to help reduce heating, cooling, and lighting loads. The Above Code Performance Case building is assumed to have a high-efficient HVAC unit roughly equivalent to the unit installed for the Advanced Performance building. Even if we were to assume that the Above Code Performance Case building was commissioned upon completion of construction, it would still not meet the mandated prerequisite energy requirements for a LEED-certified building.¹

2.4 Energy Savings for the Three Cases

When extending the savings analysis into the long term, some thought should be given to how the energy-saving features in these advanced performance office buildings degrade over time. While millions of square feet of commercial building floorspace are renovated and retrofit each year, there is relatively little public data and limited analysis that characterize these retrofits and renovations and document the energy consequences of such activities. Some designers and architectural studies have reported that a building’s skin, or the outermost layer, is modified (primarily cosmetic changes) every 20 years, while interior elements of a building are reconfigured or replaced about every 5 to 7 years (Birkeland 2002). It is not clear whether these cosmetic renovations and retrofits would potentially impact energy-related envelope features, such as the R-Values of roofs and walls. It is likely, however, that at some point in the life of an office building, some sort of retrofit would take place that would potentially impact its energy systems and usage. Figure 5 illustrates some office building retrofits that would likely occur during the course of a building’s life that would impact the building’s energy system and potentially its consumption level. These assumed retrofits are used in this analysis to characterize the projected savings levels for the High and Advanced Performance cases throughout the assumed life cycle of the building.

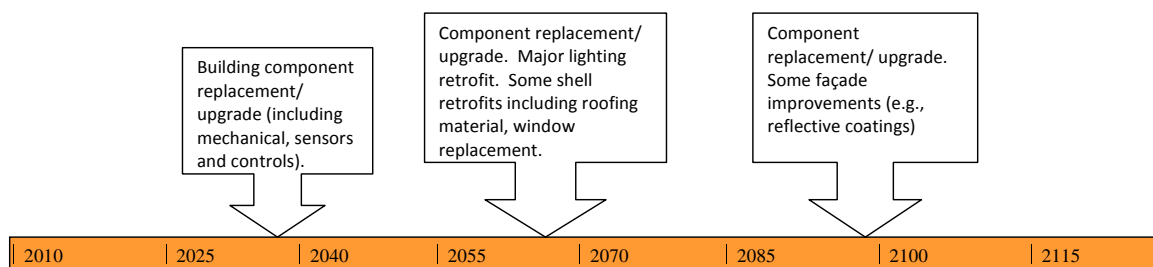


Figure 5. Likely Energy-Related Retrofits During the Life of a Commercial Office Building

¹ LEED-certified designs (Version 2.2) must earn at least two energy optimization points, which means they must be designed to reduce energy costs by at least 14% below ASHRAE Standard 90.1-2004 (USGBC 2005).

We measure savings over time by comparing the energy consumption of the hypothetical energy-efficient cases to a reference set of office buildings that are built approximately to the ASHRAE Standard 90.1-2004. Making the enabling assumption that approximately 10 million ft² of new commercial office floor space¹ is characterized as Above Code, the potential savings in a heat-load-dominated climate is estimated to be about 65 billion British thermal units (Btu) per year (Figure 6) if these buildings are built at the Above Code level rather than at code (90.1-2004). On the other hand, if this stock (10 million ft²) were characterized as the High Performance Case building, the savings would be approximately 630 billion Btu per year, and although this would decline over time, it is reasonable to assume that a portion² of the savings would be sustained such over the lifetime of the building. The Advanced Performance Case (also assumed to impact 10 million ft² of new office space) would save approximately 320 billion Btu per year in the near term, a figure that is estimated to decline to about 100 Btu per year in 2060 (i.e., assumed to maintain at least 30% of original savings level). Figure 6 shows the cumulative site energy savings of the three sets of buildings over a 100-year period.

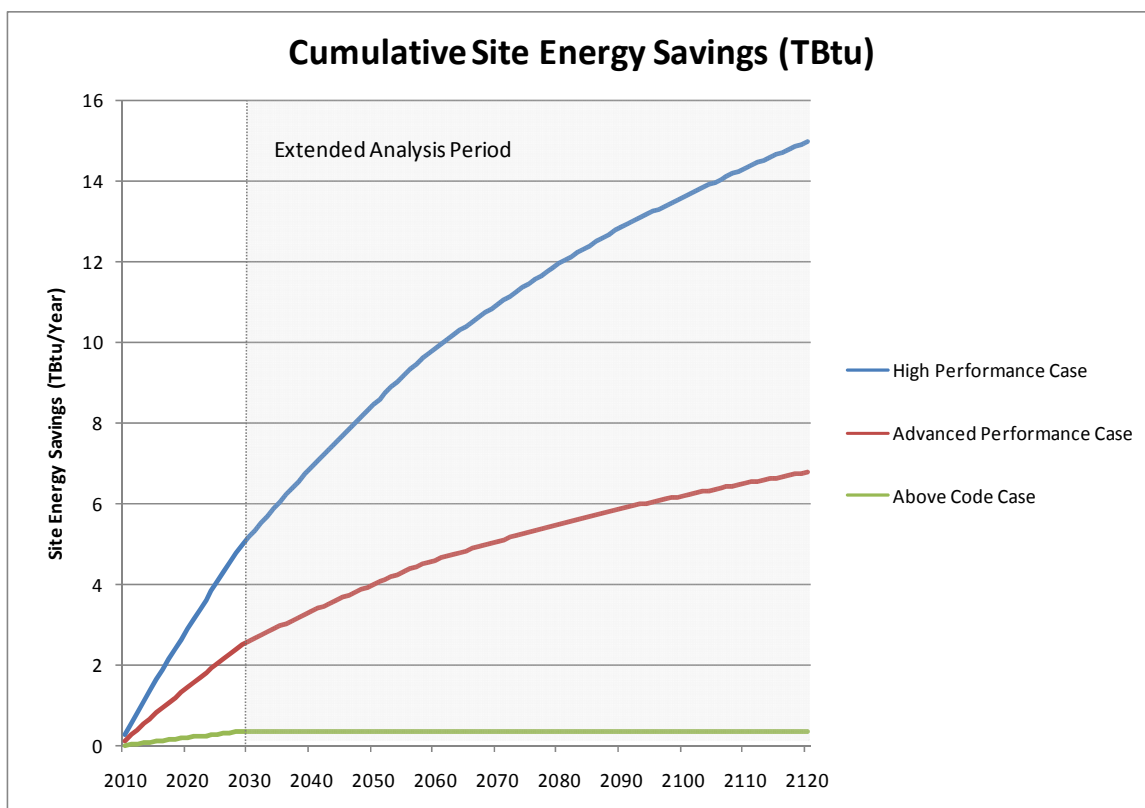


Figure 6. Savings Measured Over Time for Sample Office Building

Although high efficiency mechanical equipment can improve the savings and potentially be deployed quickly and broadly in commercial buildings, this equipment typically has a life of about 20 years. After that point, it is reasonable to assume that the equipment would potentially be replaced with something as efficient or likely even more efficient. To capture the implications of this assumption, we do not count

¹ For perspective, this would roughly reflect all the new small office floor space added to the building stock in a given year in the state of Illinois, for example.

² For the purposes of this analysis, it is assumed that 40% of the original savings amount will persist for the High Performance Case throughout the analysis period.

the energy savings attributable to the original high-efficiency equipment when the mechanical unit is retired. Therefore, the savings for the Above Code Case as shown in Figure 6 drops off at 2030. In the Advanced Performance Case, there is likely to be a more gradual degradation of savings over time due to the need for equipment replacement and major retrofits. Again, even though replacement technology would likely be something even more efficient than the technology originally installed, the relative savings attributable to DOE's CBI program would be diminished.

Based on EIA's historical trends and future projections as documented in the Annual Energy Outlook (AEO), the energy use per square foot or EUI of all building stock (including high performance) is assumed to decline over time. When renovations and retrofits occur, the savings gap between baseline practices and the High Performance Case narrows. Although the overall EUI is expected to decline over time for all buildings, the rate at which the High Performance Case EUI declines is expected to be lower than the rate of decline for standard practice and/or baseline buildings, because many of the energy-saving opportunities have already been exploited in the High Performance Case. Therefore, relative to the baseline, the energy saved with the High Performance Case will likely decline over time as equipment wears out and the gap between high efficiency and standard practice narrows. However, because of the inherent energy-optimizing design features of these buildings, a portion of the energy savings of the High and Advanced Performance office buildings are likely to be sustained, even into the very long-term.

All case results are based on the assumption that the building operation will be optimized throughout the life of the building. As noted previously, the studies related to savings persistence and actual building performance in high performance buildings would imply that this is a highly optimistic assumption. In addition, there are other unknowns. If the interior of a building is reconfigured, which some studies suggest happens approximately every 5 years, this could potentially alter the design performance of both the daylighting-optimizing and advanced HVAC features. For example, if an open-plan office that benefits from the outdoor light is sectioned off into walled offices and/or surfaces are recoated with nonreflective materials, the daylighting design benefits could be altered and likely diminished. Similarly, the use of building space is often altered. For example, if a corridor designed as a thermal flux zone is filled with cubicles, people, and equipment, the HVAC balance could be altered and a system that was once optimized may no longer operate as efficiently. In addition to physical building changes and degradation, there may be other operational and behavioral effects that impact the potential energy savings. One such effect is sometimes referred to as the "take-back" effect, which involves increased energy use concurrent with the deployment of energy-efficient measures (Granade et al. 2009).

It is likely, however, that the initial investment to design and construct a ground-source heat pump, for example, with an inherent efficiency advantage over most systems will continue to pay off in terms of energy savings well into the future. Thus, although degradation of savings is likely, a portion of savings for design-intense energy-optimizing features such as the integration of a tightened shell with daylighting optimization designs and advanced mechanical systems can potentially be sustained for the lifetime of the building.

3.0 Challenges and Uncertainties of Long-Term Analysis

Although extending the analysis into the long term has analytical appeal in terms of capturing the life cycle benefits of the program and assessing the potential impacts on carbon emissions reductions, it is not

without drawbacks. A number of logistical complications and analytical shortcomings were identified in the process of extending PNNL's BEAMS model out to 2120, as listed below:

1. Reference case complexity: We have traditionally worked with BTP Technology Development Managers to characterize BTP programs to be modeled over 20 to 30 years. Whenever possible, PNNL relies on centralized data sources, such as the AEO, CBECS, and Residential Energy Consumption Survey (RECS; all of which are developed by EIA) to develop reference forecasts. By extending the forecast out by 100 years, we were required to pull data from multiple, and potentially inconsistent, sources. These new data sources are less detailed in their building characterizations and are not updated annually, which required PNNL analytical judgment to "marry" the more specific short-term reference case to the long-term general case. In addition, multiplying these input variables by 100 vastly increases the size of input tables and pushes the limits of the underlying modeling compiler, slowing processing considerably. Appendix B contains specifics as to how the reference case was extended.
2. Bottom-up versus top-down modeling: The BEAMS model is a bottom-up accounting model that requires detailed input. Because of its structure, it is a useful tool for examining details and nuances. For example, a program modeled within BEAMS can be fine-tuned such that it targets a specific end use and equipment type within a specific building type in a specific region. Because it is able to capture these programmatic and technological nuances, it is well suited to be a short-term or possibly a mid-term modeling tool, when more is known about program specifics and the target market. When extending this model into the very long-term, however, this detailed bottom-up approach potentially introduces multiple sources of error. For example, in the year 2120 (and all intervening years), the BEAMS model requires a forecast of how many square feet in food service buildings in the north will be using electric rooftop units of some given efficiency (and so on). The fine level of detail carries with it the danger of introducing multiple errors related to data sources and the compounding of computational errors. This is typical, however, in other forecasting models that project over long time horizons, and the longer the forecast period, the less the certainty.
3. Stock and equipment turnover: Extending the analysis revealed both empirical and theoretical issues related to how to analyze and model long-term stock and building turnover. The sources and algorithms used to integrate stock turnover within the model are primarily based on 20- to 40-year periods, and simply extending these assumptions into the long term introduced some analytical imbalances that still need to be resolved. For example, neither the whole building nor envelope algorithms incorporate a lifetime variable, so any assumptions regarding the building shell are "set" for the entire analysis period, as opposed to a specified life. Additionally, envelope components are not broken out within BEAMS because they have always been assumed to last throughout the analysis period. However, the life of a window within that shell is most likely different than the life of the wall insulation. Therefore, a simple addition of "envelope component life" is significant because these nuances will need to be considered.

Another factor that must be considered is how BEAMS has historically considered building vintages. Currently, there are two sets of vintages: new and existing. New stock is anything built during the analysis period, while existing stock represents the buildings that existed prior to the analysis period. The existing stock has a built-in removal rate to account for demolition, while new stock has no such rate applied to it. Therefore, in the long-term analysis period, existing stock approaches zero, while new additions continue to rise without removal rates. A method to deal with new and existing building stock more accurately to account for building additions and removals will have to be developed.

4. Dealing with big unknowns: In the next 100 years, events will occur that we cannot predict or capture in an incremental model. There will likely be some sort of technological breakthrough—possibly in lighting or HVAC technology. These kinds of unknowns would likely best be captured in a scenario type of analysis or modeling tool. In addition, to characterize programs and technologies over a 100-year period, more thought should be given to how buildings and technologies age and how building equipment stock turns over in a long-term analytical framework.

4.0 Conclusions and Recommendations

The total potential for many new energy-efficient technologies and designs to reduce energy consumption and associated carbon emissions is substantially undervalued using an analysis period that terminates with the current AEO forecast, such as 2030. This is because new technologies are represented as incremental additions to the capital stock over time. Because some of the capital stock turns over rather slowly and because many of these programs have long-term sustaining benefits, the full impact of the program may be more adequately reflected in a “very long-term” analysis. Further, many technologies in the BTP portfolio will not be introduced for several years after the beginning of the analysis period and hence these technologies are unduly penalized under a relatively short analysis period. Thus, there is benefit to extending the time horizon of the analysis. Over time, however, the level of savings of high-efficiency buildings relative to a baseline becomes increasingly more uncertain.

Although the optimal timeframe was not determined, it is clear that uncertainties both in terms of assessing the baseline and in characterizing how buildings age over time greatly increase at about 50 years into the future. Although true for any forecast methodology, predictions of such things, such as “break-through” technologies also become wild guesses in the long term. The savings for some building R&D activities are expected to be sustained well into the future, and a forecast that only extends 20 years clearly will prematurely truncate savings. An extension to 2060 would provide 50 years of data for early adopters and also capture the peak savings level of the BTP.

5.0 References

- American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). 2004. *ASHRAE Standard Energy Standard for Buildings Except Low-Rise Residential Buildings*. ANSI/ASHRAE/IESNA Standard 90.1-2004. ASHRAE, Atlanta, Georgia.
- Ander G. 2008. “Daylighting.” Excerpted from *Whole Building Design Guide*, November 5, 2008. <http://www.wbdg.org/resources/daylighting.php>, accessed on February 22, 2009.
- Birkeland J. 2002. *Designing for Sustainability*. Earthscan, London, UK.
- Brook D. 2008. “LEED compliance not required for designing green buildings.” *Scientific America*, online special edition, October 14, 2008, available online at SciAm.com.
- Elliott DB, DM Anderson, DB Belzer, KA Cort, JA Dirks, and DJ Hostick. 2004. *Methodological Framework for Analysis of Buildings-Related Programs: The GPRA Metrics Effort*. PNNL-14697, Pacific Northwest National Laboratory, Richland, Washington. <http://www.pnl.gov/publications/>.

Energy Efficiency and Renewable Energy (EERE). 2008. *Building Technologies Program Planned Program Activities for 2008-2012*. U.S. Department of Energy, Washington D.C.

Energy Information Administration (EIA). 2009. “Commercial Sector Demand Module of the National Energy Modeling System: Model Documentation 2009.” U.S. Department of Energy, Washington D.C. May 2009. http://tonto.eia.doe.gov/reports/reports_kindD.asp?type=model%20documentation, accessed on August 2009.

Fowler KM and EM Rauch. 2006. *Sustainable Building Rating Systems Summary*. PNNL-15858, Pacific Northwest National Laboratory, Richland, Washington.

Granade, HC, J Creyts, A Derkach, P Farese, S Nyquist, K Ostrowski. 2009. *Unlocking Energy Efficiency in the U.S. Economy*. McKinsey Global Energy and Materials, McKinsey & Company. http://www.mckinsey.com/client-service/electric-power-natural-gas/downloads/US_energy_efficiency_full_report.pdf, accessed on August 2009.

Mills E. *Building Commissioning: A Golden Opportunity for Reducing Energy Costs and Greenhouse-gas Emissions*.” 2009. LBNL, Lawrence Berkeley National Laboratory, Berkeley, California. Report Prepared for: California Energy Commission, Public Interest Energy Research (PIER), July 21, 2009. Downloadable version of the report and supplementary information available at <http://cx.lbl.gov/2009-assessment.html>.

Mills E with H Friedman, T Powell, N Bourassa, D Claridge, T Hassl, and M Piette. 2004. *The Cost-Effectiveness of Commercial Buildings Commissioning: A Meta-Analysis of Energy and Non-Energy Impacts in Existing Buildings and New Construction in the United States*. LBNL No. 56637, Lawrence Berkeley National Laboratory, Berkeley, California.

National Research Council. 2001. *Energy Research at DOE: Was it Worth it?* National Academy Press, Washington, D.C.

Ryan JD and A Nicholls. 2004. “Commercial Building R&D Program Multi-Year Planning: Opportunities and Challenges.” In *Proceedings of the ACEEE Summer Study on Energy Efficiency in Buildings*, American Council for an Energy-Efficient Economy, Washington, D.C. (pp. 4-307-4-319).

Torecellini P, M Deru, B Griffith, N Long, S Pless, and R Judkoff. 2004. *Lessons Learned from Field Evaluation of Six High Performance Buildings*. NREL/CP-550-36390, National Renewable Energy Laboratory, Golden, Colorado.

Turner C and M Frankel. 2008. *Energy Performance of LEED for New Construction Buildings*. Final Report, New Buildings Institute, White Salmon, Washington.

U.S. Green Building Council (USGBC). 2005. *LEED-NC for New Construction: Reference Guide, Version 2.2*, First Edition. USBBC, Washington D.C.

U.S. Green Building Council (USGBC). 1996. “Sustainable Building Technical Manual.” Published by Public Technology Inc., Washington D.C.

Appendix A

Summary of Five Sustainable Building Rating Systems

Appendix A

Summary of Five Sustainable Building Rating Systems

Numerous building rating systems include ratings and evaluations of building energy use (either simulated or metered) and/or energy efficiency measures. A 2006 Pacific Northwest National Laboratory (PNNL) study completed for the U.S. General Services Administration reviews 30 sustainable building rating systems, and identified five design rating systems that focus on a whole building evaluation (rather than individual design features), provide clear ways to assess building design, and were applicable to common commercial building types in the U.S. market.

Of the 30 rating systems screened, detailed information was provided for five design rating systems, including criteria that specifically address optimizing energy usage design in the buildings. Approximately 20% to 35% of all the points earned as part of the rating system are directly linked with energy optimization. In addition, energy efficiency and usage can indirectly be impacted by other rating categories such as water conservation, site optimization, and operational and maintenance practices. All programs focus on reducing overall building energy consumption through energy-demand minimization measures, energy-efficient systems, and “right sizing” of equipment, and all include credit for various renewable sources of energy. The following provides a brief description of each of these five rating systems and some of the energy measurement and optimization criteria included as part of these systems (Fowler and Rauch 2006):

- **Building Research Establishment’s Environmental Assessment Method (BREEAM):** Developed in the United Kingdom in 1990, BREEAM is the building environmental assessment method with the longest track record. Energy use is measured and validated through sub-metering.
- **Comprehensive Assessment System for Building Environmental Efficiency (CASBEE):** Developed in 2001 in Japan, the CASBEE rating system distinguishes the environmental load (in terms of energy and water usage, materials, environmental impact and pollution, etc.) from the quality of building performance and relates these two factors plotted on a graph, with environmental load on one axis and quality on the other. The “best” buildings will fall in the section representing lowest environmental load and highest quality.
- **GBTool:** GBTool was developed by the International Framework Committee for the Green Building Challenge, an international project that has involved more than 25 countries since 1998. For GBTool, life cycle analysis was used as the basis for the embodied energy criteria. Energy consumption is assessed through total use of nonrenewable energy (embodied and operational), electrical peak demand for operations, use of renewable energy, and commissioning.
- **Green Globes™ U.S.:** Green Globes™ U.S. was adapted from the Green Globes Canada rating system in 2004 and is an online tool designed for use by architects and builders for any size commercial building. Approximately 36% of Green Globes™ U.S. points are earned through energy-optimization measures, which focus on energy-demand minimization, energy-efficient systems, and renewable sources of energy.
- **Leadership in Energy and Environmental Design (LEED):** LEED was developed and piloted in the United States in 1998 as a consensus-based building rating system by U.S. Green Building Council

(USGBC) member committees. The rating system addresses specific environmental building-related impacts using a whole building environmental performance approach. Approximately 25% of the points that can be earned are directly related to energy optimization. All LEED-certified buildings are required to meet certain minimal building energy design standards (14% better than the American Society of Heating, Refrigerating, and Air-Conditioning [ASHRAE] Standard 90.1-2004) and building energy commissioning is mandatory. Additional points are given for daylighting, occupant controls and thermal comfort design strategies. Energy modeling is required for all LEED projects unless the prescriptive approach of following the Advanced Energy Design Guides is chosen.

Only two of these systems (Green Globes™ U.S. and LEED) have a U.S.-specific version; however, the remaining three have versions that can and have been applied to the U.S. market. LEED is currently the dominant system in the United States market and is being used in 91 countries. A publically available Product Development and Maintenance Manual governs how changes are made to the LEED rating system. The steps followed for the development of USGBC rating system products include technical development by committee, pilot testing, public comment period, approval by council membership, and then release for public use. Documentation of the quantifiable energy design measures are provided to the USGBC, the developer of the LEED rating system, for third-party verification. The assessors have been trained and must pass an examination.

Appendix B

Extension of Reference Case

Appendix B

Extension of Reference Case

The original reference case contained in the Building Energy Analysis and Modeling System (BEAMS; through 2030) relies primarily upon data from the Energy Information Administration, including the National Energy Modeling System (NEMS), Commercial Buildings Energy Consumption Survey (CBECS), and Residential Energy Consumption Survey (RECS), although other sources are also used. Extending the reference case required some thought, because the requirements included data consistency as well as citable sources. The reference case contains the following data sets:

- building stock forecast (by building type, vintage, and region)
- equipment efficiencies and market shares (by building type and region)
- base loads (by building type, vintage, and region)
- emissions factors and water factors (applicable to all types)
- electricity conversion factors (applicable to all types)
- fuel prices (by building sector).

The extension of each of these data sets is discussed in the following sections.

B.1 Building Stock

The building stock forecast was developed by extending the Annual Energy Outlook's (AEO's) current forecast (to 2030) linearly by principal activity out to 2120. Projections for the split between new and existing commercial stock were also extended based on the current assumptions for removal rates.

B.2 Equipment Efficiencies and Market Shares

For equipment efficiencies and market shares pertaining to heating, cooling, and water heating, PNNL used data from the MiniCAM model, a global, integrated assessment model of energy, agriculture, greenhouse gas concentrations, and climate change (Clark et al. 2007). MiniCAM's inputs are developed in 15-year increments from 1990 through 2095, for a more generic set of equipment types.

Equipment shares through 2030 were developed using NEMS projections and CBECS data. To develop a forecast through 2120, the MiniCAM equipment types were disaggregated when necessary, based on the share of equipment in 2030 from the NEMS/CBECS forecast. For example, MiniCAM contains heating shares for electric heat pumps and electric furnaces/boilers, while the NEMS/CBECS forecast includes electric heat pumps, boilers, furnaces, individual space heaters heat, packaged units, and other electric heating. Therefore, the MiniCAM share for heat pumps would have been assigned to the heat pump category, while the furnace/boiler share was divided into the other categories, based on share in 2030. The 2095 end point was used to develop trend lines using a polynomial function, and then those equations were applied to develop an annual forecast (Figure B.1). Both NEMS and MiniCAM use a forecast of energy prices, among other factors, so the resulting market shares projected from these models depend on the underlying assumptions about energy supply and demand within the United States.

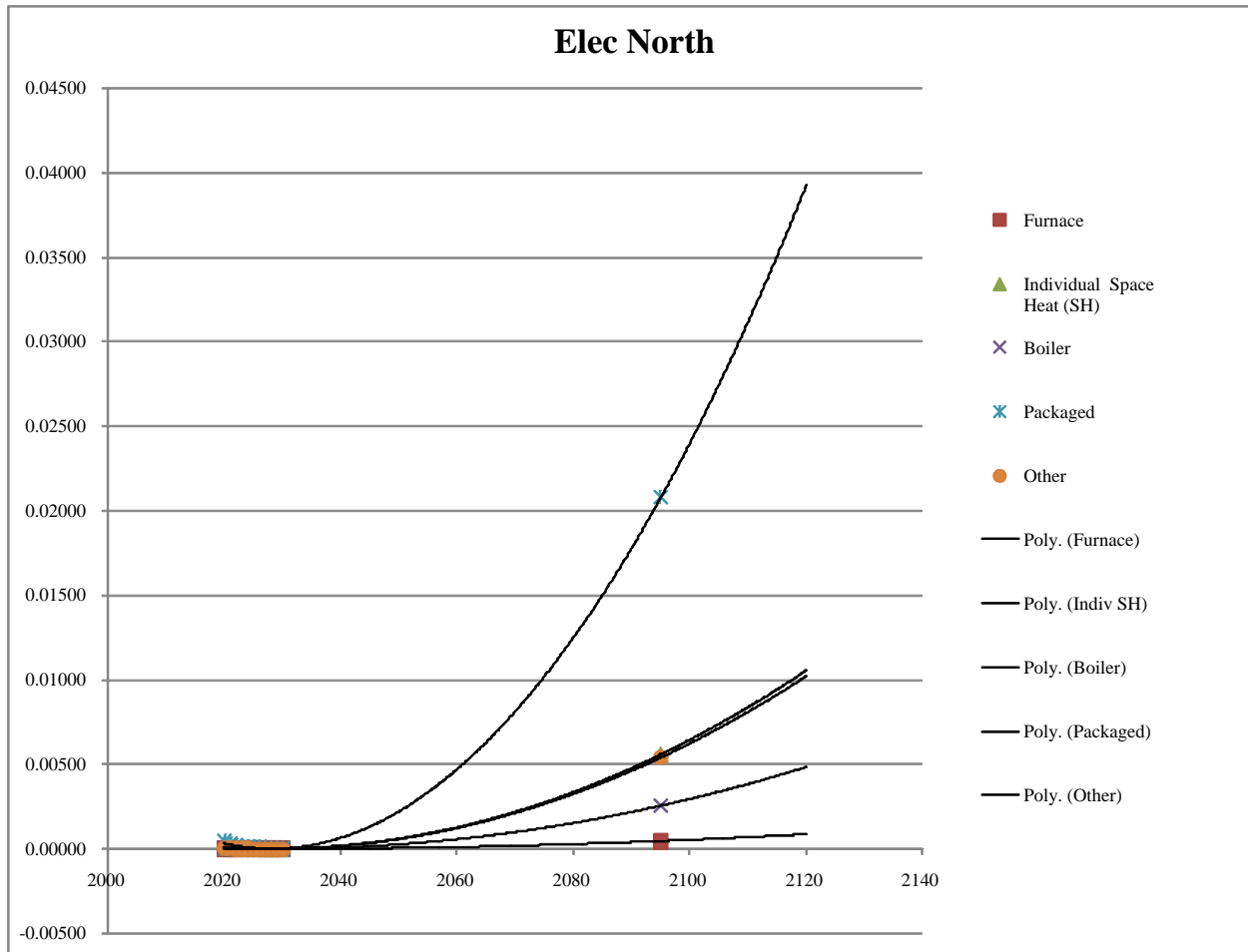


Figure B.1. Example Trend Line Plot to Forecast Market Shares for Electric Heating in the North (excludes electric heat pump)

Equipment efficiencies were taken from MiniCAM, linearly interpolated, and entered directly into BEAMS.

For lighting, representative building type aggregate illuminance levels (in footcandles) were developed using the ASHRAE/Illuminating Engineering Society of North America (IES) Standard 90.1 analysis models that include data from the PNNL NC3 data set (Richman and Rauch 2007). The models were reconfigured to calculate light levels associated with meeting the 90.1 criteria based on IES lighting recommendations.

Current lighting technology percentages by building type were developed from current building lighting data available in the PNNL NC3 data set. Future projections were developed from a combination of current replacement and retrofit trends and expected future efficacy improvements.

Current and vintage lamp efficacies were developed using recent product analysis performed for federal lamp efficiency rulemaking efforts. These values represent typical current product characteristics. The generic lighting efficacies were calculated by fitting the building level efficacy and adjustment

factors to the technology specific data for 2010, 2020, 2030, and 2050 to calculate a trend lines (typically a power fit) for each piece (efficacy and adjustment factor). These are then projected out to 2120.

B.3 Base Loads

Base loads were updated with energy use information derived from the Facility Energy Decision System (PNNL 2008) to reflect current and projected energy technology and consumption behavior. Lighting and miscellaneous equipment inputs were derived from MiniCAM inputs.

B.4 Emissions Factors, Water Factors, and Electricity Conversion Factors

Emissions factors, water factors, and electricity conversion factors were developed using MiniCAM assumptions about electricity generation, heat rates, and fuel mixes.

B.5 Fuel Prices

The fuel price forecast was extended using assumptions from the MiniCAM model. Because the MiniCAM model uses natural gas prices at the wellhead, instead of the price to the buildings sector, the average difference between AEO's wellhead forecast and building price forecast was applied to yield a comparable natural gas price forecast.

B.6 References

Clarke LE, MA Wise, SH Kim, SJ Smith, J Lurz, JA Edmonds, and HM Pitcher. 2007. *Model Documentation for the MiniCAM Climate Change Science Program Stabilization Scenarios: CCSP Product 2.1a*. PNNL-16735, Pacific Northwest National Laboratory, Richland, Washington.

Pacific Northwest National Laboratory (PNNL). 2008. *Facility Energy Decision System User's Guide, Release 6.0*. PNNL-17848, Pacific Northwest National Laboratory, Richland, Washington.

Richman EE and EM Rauch. 2007. *The Expansion of the National Commercial Construction Characteristics NC3 Database to Support Benchmarking Analysis*. PNNL-SA-58002, Pacific Northwest National Laboratory, Richland, Washington.



Proudly Operated by Battelle Since 1965

902 Battelle Boulevard
P.O. Box 999
Richland, WA 99352
1-888-375-PNNL (7665)

www.pnl.gov



U.S. DEPARTMENT OF
ENERGY