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Pacific Northwest National Laboratory
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Methodological Framework for Analysis of Buildings-Related Programs: The GPRA Metrics Effort

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Prepared for the U.S. Department of Energy
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Summary

The requirements of the Government Performance and Results Act (GPRA) of 1993 mandate the reporting of outcomes expected to result from programs of the federal government. The U.S. Department of Energy's (DOE's) Office of Energy Efficiency and Renewable Energy (EERE) develops official metrics for its 11 major programs using its Office of Planning, Budget Formulation, and Analysis (OPBFA). OPBFA conducts an annual integrated modeling analysis to produce estimates of the energy, environmental, and financial benefits expected from EERE's budget request.

Two of EERE's major programs include the Building Technologies Program (BT) and Office of Weatherization and Intergovernmental Program (WIP). Pacific Northwest National Laboratory (PNNL) supports the OPBFA effort by developing the program characterizations and other market information affecting these programs that are necessary to provide input to the EERE integrated modeling analysis. Throughout the report we refer to these programs as "buildings-related" programs because the approach is not limited in application to BT or WIP.

To adequately support OPBFA in the development of official GPRA metrics, PNNL communicates with the various activities and projects in BT and WIP to determine how best to characterize their activities planned for the upcoming budget request. PNNL then analyzes these projects to determine what the results of the characterizations would imply for energy markets, technology markets, and consumer behavior. This is accomplished by developing nonintegrated estimates of energy, environmental, and financial benefits (i.e., outcomes) of the technologies and practices expected to result from the budget request. These characterizations and nonintegrated modeling results are provided to OPBFA as inputs to the official benefits estimates developed for the federal budget.

This report documents the approach and methodology used to estimate future energy, environmental, and financial benefits produced by technologies and practices supported by BT and by WIP. However, the approach is general enough for analysis of buildings-related technologies, independent of any specific program. An overview describes the GPRA process and the models used to estimate energy savings. The body of the document describes the algorithms used and the diffusion curve estimates.

Acronyms

AFUE	annual fuel utilization efficiency
AAMA	American Architectural Manufacturers Association
BEAMS	Building Energy Analysis and Modeling System
BT	Office of Building Technologies Programs
BTS	Office of Building Technology, State and Community Programs
CBECS	Commercial Buildings Energy Consumption Survey
CFL	compact fluorescent lights
CO	carbon monoxide
COP	coefficient of performance
DOE	U.S. Department of Energy
EER	energy efficiency ratio
EERE	Office of Energy Efficiency and Renewable Energy
EF	energy factor
EIA	Energy Information Administration
EPAct	Energy Policy Act of 1992
EPRI	Electric Power Research Institute
EREC	Energy Efficiency and Renewable Energy Clearinghouse
FEDS	Facility Energy Decision System
FRHOB	flame retention head oil burners
GAMA	Gas Appliance Manufacturers Association
GPRA	Government Performance and Results Act of 1993
IECC	International Energy Conservation Code
kBtu	thousand Btu
LBNL	Lawrence Berkeley National Laboratory
LTS	Lincoln Technical Services
MMBtu	million Btu
MMTCE	million metric tons carbon equivalent
MMton	million metric tons
NEMS	National Energy Modeling System
NOx	nitrous oxides
ORNL	Oak Ridge National Laboratory
PBFA	Office of Planning, Budget Formulation, and Analysis
PM	particulate matter
PNNL	Pacific Northwest National Laboratory
QBtu	quadrillion Btu
R&D	research and development
RECS	Residential Energy Consumption Survey
SCOP	seasonal coefficient of performance
SEER	seasonal energy efficiency ratio
SO2	sulfur dioxide
TBtu	trillion Btu
VOC	volatile organic compound
WIP	Office of Weatherization and Intergovernmental Programs

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1.0 Overview of PNNL's GPRA Metrics

The requirements of the Government Performance and Results Act (GPRA) of 1993 mandate the reporting of outcomes expected to result from programs of the Federal government. The U.S. Department of Energy's (DOE's) Office of Energy Efficiency and Renewable Energy (EERE) develops official metrics for its 11 major programs using its Office of Planning, Budget Formulation, and Analysis (OPBFA). OPBFA conducts an annual integrated modeling analysis to produce estimates of the energy, environmental, and financial benefits expected from EERE's budget request.

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1.1 Estimating the Energy Savings of Buildings-Related Projects

No single model or approach is capable of capturing or adequately representing the diversity of activities supported by BT and WIP (not to mention the rest of the EERE portfolio). As such, PNNL has adopted a variety of analytical approaches including macro economic models, energy accounting models, and spreadsheets. This section briefly describes the analytical approaches used to estimate energy savings for BT and WIP.

PNNL reports the benefits of BT and WIP projects and technologies at several different levels: they are provided at the program (BT and WIP) level for use by senior EERE management in considering portfolio options, at the decision unit level for use by Program Managers to assess program direction and future progress toward goals and objectives, and at the project/activity level for use by project managers in planning and execution.

PNNL assessed the benefits for a limited number of defined metrics:

- energy savings
- environmental benefits
- economic/financial metrics.

The buildings-related projects produce many other benefits, including reductions in peak energy loads, enhanced security due to reduced oil demand, reduced energy costs for low-income households, and increased comfort and health in buildings; however, these are not currently measured as part of the GPRA process.

The environmental impacts that are estimated as part of the GPRA process are only those directly related to the burning of fossil fuels; other impacts such as land use and localized water pollution are not measured. Within the economic metrics, the consumer cost savings (or energy cost savings) simply reflect monetization of the energy savings and do not include the incremental cost of the new technology or practice; nor are they discounted. For both the environmental impacts and consumer cost savings, calculations are based on EERE guidance for the GPRA Metrics effort (Draft letter, Office of Energy Efficiency and Renewable Energy. April 1, 2002. "Performance Planning Guidance (GPRA Data Call) FY 2004-FY 2008 Budget Cycle." US Department of Energy, Washington, D.C.). Because environmental and economic benefits (energy cost savings) relate directly to projected energy savings, the balance of this overview focuses on just estimates of energy savings.

The benefit estimates are based on an evaluation of each project to determine the impact of successful project implementation (in other words, each project is assumed to meet its' stated goals). Our analysis considered project goals, technology characteristics (including performance and cost), the targeted market, and project milestones. Not all activities result in readily measurable energy savings as they are intermediate or enabling technologies or practices, or are contributing to the basic understanding (a "knowledge" benefit) of energy use in the building sector. For this GPRA analysis, we selected activities for which it was possible to develop measured energy savings.

The benefit estimates are developed based on a series of assumptions developed project-by-project. These input assumptions are critical to the analysis and are developed through an iterative process with the project managers. Note that because BT and WIP projects are in different stages of maturity, there are varying degrees of corroborative studies available on which project information can be substantiated. Additionally, newer projects may not have estimates of future costs well-coordinated with performance estimates. For example, research projects would be expected to have more tenuous estimates of price and performance characteristics of potential products than deployment-related projects that feature products closer to market adoption. PNNL recognizes the varying levels of maturity and distance from market across projects and that the cost and performance characteristics improve as projects mature or as they near commercialization.

1.2 Modeling Methods Used in Estimating Benefits

PNNL calculated the buildings-related BT and WIP GPRA nonintegrated estimates of benefits using one of three methods:

- a PNNL adaptation of the National Energy Modeling System (NEMS-PNNL)[a]
- Building Energy Analysis and Modeling System (BEAMS)[b]
- spreadsheets designed for a specific project.

NEMS-PNNL allows the costs and benefit characteristics of a technology and its market penetration to be linked. However, NEMS-PNNL has difficulty representing some technologies, such as the whole-building projects (projects that use a systems approach, looking at integration and interaction of building components such as roofs, walls, and equipment and seeking to optimize energy efficiency through consideration of these interactions), because NEMS-PNNL is designed to model specific technologies, not the impacts of groups of interacting technologies.

BEAMS was built specifically for estimating the benefits of building-related projects and therefore allows various types of projects to be characterized, including whole-building, envelope, and equipment projects. A disadvantage of the BEAMS model is its reliance on externally-determined penetration rates (i.e., fraction of sales or fraction of installed base). Analyst judgment combined with available market information was used to construct the penetration functions used to model technology or project impacts. In addition, BEAMS cannot model equipment that competes against more than one baseline equipment type.

To aid in the development of external penetration rates, PNNL conducted a study to examine the historical market penetration (i.e., diffusion) for 10 energy-efficient products related to the buildings sector. Section 3.0 provides the most complete report of that study. PNNL estimated diffusion models for each product based on the specification proposed by F.M. Bass (1969). Bass was the first to suggest the S-curve or logistical functional form for the market diffusion of new products, and his concepts are still widely used in the marketing discipline today. PNNL incorporated the resulting models into the GPRA metrics analysis for many of the projects and technologies not modeled within the NEMS framework and designed the model development and empirical analysis to generate more credible predictions of the adoption process of important energy-efficiency technologies in the buildings sector. The technologies were placed into four separate categories: lighting; heating, ventilation, air-conditioning and refrigeration (HVAC/R); envelope; and other.

PNNL used spreadsheets to model projects not easily modeled in BEAMS or NEMS-PNNL. For example, because some projects previously had developed their own set of spreadsheet tools for estimating impacts, PNNL adapted these tools for the GPRA estimation process. We describe each of the three methods used for deriving energy-saving estimates in more detail in Section 2.0 of this document.

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[a] Any modification or alteration to the official NEMS model must be called out as such; for PNNL's GPRA effort, the modified version used is referred to as NEMS-PNNL.

[b] The BEAMS model was previously known as BESET

1.3 The National Research Council Methodology

A National Academy of Sciences report (NRC 2001) assessed the outcomes of energy efficiency and fossil energy research from 1978 to 2000. One of the council's recommendations for assessing research development and deployment projects was that "DOE should adopt an analytic framework similar to that used by this committee as a uniform methodology for assessing the benefits and costs of its R&D projects. DOE should also use this type of analytic framework in reporting to Congress under GPRA."

The National Research Council (NRC) committee assumed that the private sector would have developed the technology in the absence of DOE five years after DOE realized the benefits (also known as the "5-year rule"). This assumption was made in order to more readily compare the impact of the various technologies analyzed, and was not based on empirical evidence or theory that most government efforts merely accelerate introduction of technologies into the marketplace. It should be noted that the NRC studied only research and development (R&D) projects, so universal adoption of the 5-year rule by all projects, such as rulemaking and information efforts, goes beyond the NRC's intent. As such, this assumption was adopted, in part, as part of the uniform process for assessing prospective (future) benefits of EERE programs. However, alternative acceleration periods are assumed on a case-by-case basis.

The calculation methodologies for the projects characterized using the National Research Council methodology were modified to remove the estimated benefits that would have occurred in the absence of DOE funding. This change was implemented within the buildings-related estimates by determining the projects that act as acceleration-to-market activities rather than projects that would not have been developed or implemented in the absence of government funding (some projects, such as Weatherization Assistance and Appliance Standards, would most likely not be undertaken by the private sector and therefore do not have a form of the 5-year rule applied to them). This approach diminishes the project savings in future years, presuming that the private sector is expanding its development and production of these technologies. Figure 1-1 illustrates how applying this acceleration methodology impacts a project's estimates in its most simplified state. Note that the bell-shaped curve in Figure 1-1 depicts the difference (the net benefit from DOE R&D, also shown as the shaded area) between the penetration without DOE R&D and the accelerated penetration with DOE R&D.

1.4 Baseline Inputs

The nonintegrated benefits estimates produced for the GPRA effort represent the estimated future impacts of activity funding. In order to produce the estimated impacts, baseline forecast assumptions must first be established. To the extent possible, the underlying assumptions about building stock forecasts, future equipment efficiencies, future market shares, and future end-use loads were consistent across tools (i.e., NEMS-PNNL, BEAMS, and spreadsheets). We accomplished consistency by drawing most of the baseline characterization data from forecasts produced by the Energy Information Administration (EIA), a statistical agency within DOE. For example, the same version of NEMS used to develop the FY 2005 estimates was used to produce EIA's *Annual Energy Outlook 2003*.

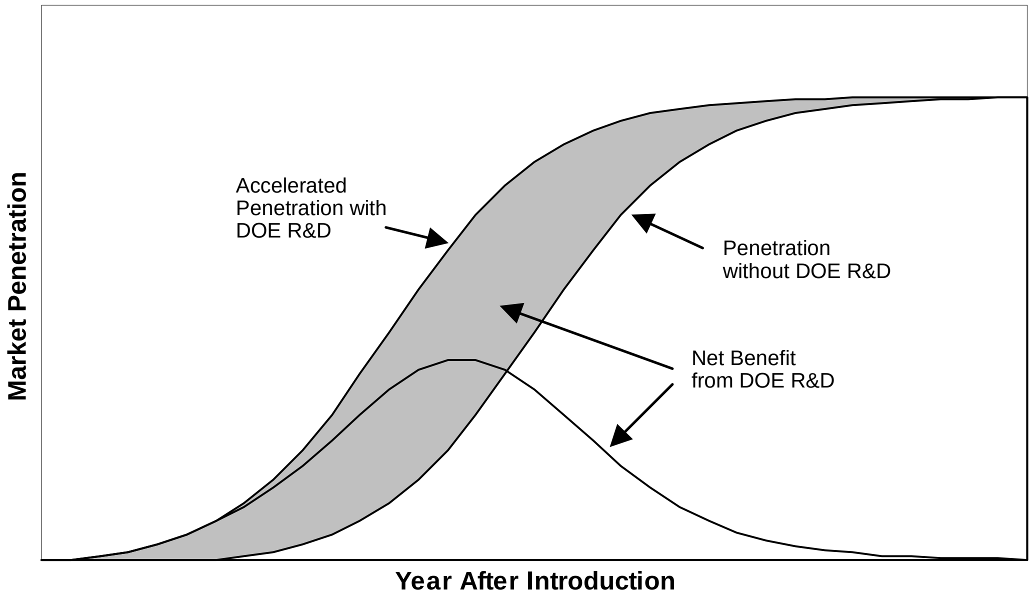

Figure 1.1. Impact of National Research Council Methodology (pure market acceleration case)

BEAMS also has a baseline forecast characterization, which is drawn from NEMS-PNNL, EIA's *Annual Energy Outlook*, the 1997 "Residential Energy Consumption Survey," and the 1999 "Commercial Buildings Energy Consumption Survey." PNNL verified the consistency of the baseline assumptions of the spreadsheet tools against EIA's data. Baseline data are updated as newer versions of these documents are released and incorporated into EIA's version of NEMS.

1.5 Adjustments to Estimates due to Budget Revisions

The budget formulation process involves much iteration, and the budget requested for various line items may change during that process. First, EERE develops an initial budget; next, an internal review budget is developed in conjunction with the Chief Financial Officer; eventually, the budget proceeds to the Office of Management and Budget (OMB), and subsequent versions are developed based on an appeal of the OMB pass back. Finally, the budget is formally submitted by the President to Congress (referred to in this document as the final budget request).

The project characterizations driving the benefits estimates are developed through close interaction with the BT and WIP project managers. The characterizations require the DOE project manager to make assumptions based on the requested level of funding, and the characterization then describes what would be accomplished at that level. However, because the budget request amount sometimes changes between the time that the characterization is developed and the time that the budget request is finalized, and also because changes occur between the final budget request (on which the final estimates are based) and the actual allocation, PNNL needs to be able to quickly recalculate the estimated benefits for the various projects.

For small changes in budget levels, PNNL introduces a basic "budget adjustment" to the project estimates. We assume that to get to X savings, a total of Y budget must be spent, where Y is the cumulative budget over the projection period. A change in the annual budget results in a change in the cumulative budget. Revised savings are calculated for each year using the formula: new cumulative budget in year z divided by old cumulative budget in year z. This adjustment mechanism implicitly suggests that either the fraction of expected sales or the performance of the project has changed but does not explicitly tie the change to one factor or the other.

For larger changes, we revisit the project inputs with the DOE project managers to determine the impact of a reduced (or increased) budget. Options for adjusting the models include changing the year of market introduction, changing the impact on sales (market penetration), modifying the performance objective, and adding or removing tasks or technologies within the project.

1.6 Contents of this Document

The remainder of this document consists of four sections. Section 2.0 provides more detailed information on the methodology behind the development of the GPRA benefits estimates. Section 3.0 provides more detailed information on the technology diffusion curves, and Section 4.0 lists the references for the document.

2.0 GPRA Metrics Methodology

This section describes the calculation methodology used within BEAMS, NEMS-PNNL, and spreadsheets to estimate the energy savings for buildings-related projects.

2.1 BEAMS Methodology

BEAMS is a bottom-up accounting model that compares baseline energy use against specific EERE-sponsored technologies. BEAMS also is used to centrally collect, store, and report all results produced by all the various estimation methods. In addition to energy savings forecasts, these results also include such items as associated emissions reductions and necessary investment.

BEAMS can estimate benefits for various projects: whole-building, envelope, lighting, HVAC, and water heating. BEAMS is used primarily to model projects that target whole-building energy use or envelope (building shell) improvements. Although BEAMS can model equipment projects, those projects are primarily estimated using NEMS-PNNL.

To determine energy savings for specific buildings-related projects, BEAMS requires information in the following areas:

- **Project Performance Goals.** The goals of each project are assessed in terms of energy savings (e.g., percent load reductions and equipment efficiency improvements) and used as inputs to BEAMS. PNNL gathers this information from each project by interviewing the project manager or reviewing project literature (e.g., technical reports, brochures, and websites).

- **Target Market.** Target markets are defined in terms of building sector (e.g., residential and commercial), building type (e.g., single family and educational), size (commercial only), income level (residential only), vintage (e.g., new or existing), and climate zone or region. Figure 2.1 illustrates the process used to define the project's targeted market segment within BEAMS, where certain building types, and building sizes are excluded from the mix (indicated with arrow curving downward), leaving a more specific market to target.

  Once the target market has been identified, PNNL determines penetration into that market using technology diffusion curves (discussed in Section 3.0). Within BEAMS, market penetration is defined as either the fraction of sales for equipment and lighting projects or the fraction of installed base for envelope and whole-building projects. The penetration model requires only the year of introduction into the market, an estimate of market penetration in 2020 (provided by BT and WIP project managers), and the selection of the most appropriate diffusion curve category (e.g., lighting or HVAC).

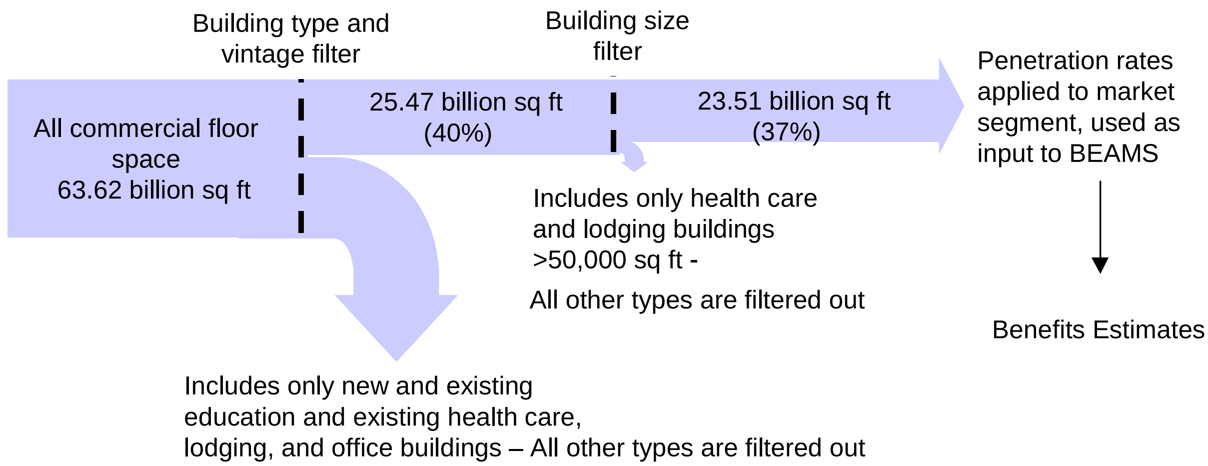

Figure 2.1. Developing the Market Segment (BEAMS)

- **Private Investment (cost).** Estimates of private investment for both the baseline and the EERE technology or practice are entered into BEAMS. Ideally, the investment costs would be considered when market penetration is developed; however, the current diffusion model used does not incorporate costs at this time. In addition to private investment, non-energy project benefits are also quantified when possible and entered into BEAMS.

All site-level energy savings and investment estimates are aggregated through a BEAMS–to NEMS-PNNL interface. After this aggregation, BEAMS calculates the primary energy savings, associated emissions reductions, and the dollar value of the energy savings. BEAMS contains a report generator that aggregates the project- and technology-level benefits into the decision units. Each of the BEAMS algorithm approaches is further documented below.

2.1.1 Whole-Building and Envelope Project Approach

This section addresses projects that target the building envelope or use a whole-building design approach. Envelope projects are modeled as improvements to the building envelope (shell measures, such as improvements to wall insulation and windows), whereas whole-building projects impact the total building system. Envelope and whole-building projects are both characterized by a reduction in space conditioning and/or water heating load resulting from changes in the building system or envelope. Additionally, whole-building projects may also result in reductions in lighting consumption.

Calculating the energy savings associated with envelope and whole-building projects involves the following steps, which are discussed in the next subsections:

- Determine the size of the potential market.
- Determine the number of units affected by the buildings-related project.
- Determine the base end-use loads.
- Determine the end-use loads after project implementation.
- Calculate the energy savings.

2.1.1.1 Determine Size of the Potential Market

Building stock estimates are used to determine the potential market for each project.
Residential and commercial new and existing building stock totals for all years through FY 2025 were provided by the latest version of EIA's *Annual Energy Outlook*. The years 2026 through 2030 were extrapolated based on the annual growth from 2001 through 2025. The stock estimates have been developed for each market segment (e.g., building type, building vintage, and region) based on several assumptions bulleted below.

The building stock was disaggregated into north and south regions by using the EIA climate zones published in the "Residential Energy Consumption Survey" (EIA 1997) and the "Commercial Buildings Energy Consumption Survey" (EIA 1995, 1999). Climate zones 1 through 3 (i.e., zones with >4,000 heating-degree days) were designated as the north region, and zones 4 and 5 (i.e., zones with <4,000 heating-degree days) were defined as the south regions. Using this method, approximate percentages of north and south existing units and new construction were estimated:

- Residential single-family and multifamily housing
  - 60% of the existing building stock is in the north.
  - 40% of the existing building stock is in the south.
  - New stock is divided evenly across regions.

- Residential manufactured housing
  - 48% of the existing building stock is in the north.
  - 52% of the existing building stock is in the south.
  - 45% of the new building stock is in the north.
  - 55% of the new building stock is in the south.

- Commercial buildings
  - 59% of the existing building stock is in the north.
  - 41% of the existing building stock is in the south.
  - 55% of the new building stock is in the north.
  - 45% of the new building stock is in the south.

Using the assumptions listed above, the building stock numbers were segmented by building vintage and region. Using the budget year as the base year, PNNL classifies all construction beginning with the base year as new.

Each envelope or whole-building project has a specified target market: residential and/or commercial (and their subsets), new and/or existing vintages, and north and/or south regions. The potential market for any project is the set of targeted buildings. For example, a project targeting single-family construction includes only the forecasts for new and existing single-family construction in the north and south.

2.1.1.2 Determine Number of Units Affected by the Buildings-Related Project

The number of units affected by the buildings-related project is calculated using the fraction of installed base (penetration rate) that the project is expected to capture and the building stock. A penetration rate is applied to the appropriate market segment to compute the number of units impacted by the buildings-related project, as follows:

$$u_{s,b,v,r,t} = P_{s,b,v,r,t} \times S_{s,b,v,r,t} \tag{2-1}$$

Where $u_{s,b,v,r,t}$ = number of units affected in year *t* (billion ft^2 or million households) for building sector *s*, building type *b*, vintage *v*, and region *r*

$P_{s,b,v,r,t}$ = penetration rate in year *t* for building sector *s*, building type *b*, vintage *v*, and region *r*

$S_{s,b,v,r,t}$ = building stock in year *t* (billion ft^2 or million households) for building sector *s*, building type *b*, vintage *v*, and region *r*.

All equations in the BEAMS methodology section are broken out by building sector, type, vintage, and region. To keep the subsequent equations readable, the subscripts for these categorizations are omitted.

For new building stock, which represents annual construction, the product in Equation 2-1 provides the number of impacted units in year *t*. However, for existing buildings, this calculation actually yields a cumulative number, as represented below in Equation 2-2:

$$U_t = \sum_{i=1}^{t} u_i \times \frac{S_t}{S_i} \tag{2-2}$$

Where U_t = cumulative surviving units impacted through year *t*

u_i = number of units impacted in year *i*

S_t = building stock in year *t*

S_i = building stock in year *i*.

Within BEAMS, the existing building stock is defined as the total stock at the beginning of the base year, which subsequently gradually declines over time through events such as fires and demolition. The total units affected at time *t* for existing buildings are, in effect, cumulative to that time period because penetration occurs against that same, entire (although gradually declining) stock each year. As a result, the number of existing-vintage installed units by year must be disaggregated, while also accounting for the effects of declining building stock on units from previous years. In other words, only the incremental units affected in a given year should be captured, and this additional step ensures that that occurs. Equation 2-3 explicitly shows this step that addresses the problem of cumulative units for existing vintage buildings:

$$u_t = U_t - \left(U_{t-1} \times \frac{S_t}{S_{t-1}} \right) \text{for t} > 1 \tag{2-3}$$

2.1.1.3 Determine Base End-Use Loads

End-use loads represent the baseline service requirements per square foot (commercial) or per household (residential) for heating, cooling, water heating, and lighting. The units for commercial building loads are kBtu/ft^2, or in the case of lighting, thousand lumen-hours/ft^2. For residential buildings the corresponding units are MMBtu/household and million lumen-hours/household. Baseline end-use loads are distinguished by building types (e.g., assembly, education, multifamily) as well as by vintage and climate zone. End-use loads were updated in June 2000 with energy use information derived from the Facility Energy Decision System (FEDS) software to reflect current energy technology and consumption behavior.

The performance improvements for envelope and whole-building projects are characterized by reductions in the end-use loads. Therefore, the base energy consumption does not have to be explicitly calculated. Instead, the load reduction is applied to the base load to determine the new load, and the resulting difference in loads is used to calculate energy savings.

2.1.1.4 Determine End-Use Loads After Project Implementation

The performance inputs for envelope and whole-building projects are defined in terms of percent load reductions. The load reductions are applied to the corresponding end-use load segment to determine the building-level load reductions by end use, as follows:

$$lr_{e,t} = L_{e,t} \times R_{e,t} \tag{2-4}$$

Where $lr_{e,t}$ = building-level load reduction (in kBtu/ft^2 or MMBtu/household, or in the case of lighting, thousand lumen-hours/ft^2 or million lumen-hours/household) in year *t* for end-use *e*

$L_{e,t}$ = load in year *t* (kBtu/ft^2, MMBtu/household, thousand lumen-hours/ft^2, or million lumen-hours/household) for end-use *e*

$R_{e,t}$ = percent load reduction in year *t* (provided in the project characterization) for end-use *e*.

The building-level load reductions are translated into aggregate load reductions by region as follows:

$$LR_{e,t} = lr_{e,t} \times u_t \quad (2\text{-}5)$$

Where $LR_{e,t}$ = regional load reduction in year *t* for end-use *e* (TBtu, or for lighting, trillion lumen-hours)

$lr_{e,t}$ = building-level load reduction in year *t* for end-use *e*

u_t = total number of units impacted in year *t* (calculated in Equation 2-3 [existing] or Equation 2-1 [new]).

At this point, these potential load reductions are cumulated across years of the analysis. Each installation under the project continues to have savings impacts beyond the initial year of installation. The calculations, as shown in the equations below, provide aggregate load reductions in each year, while taking into account the effect of declining building stock for existing buildings. This declining building stock acts to reduce savings somewhat over time. For existing buildings:

$$CLR_{e,t} = \sum_{i=1}^{t} LR_{e,i} \times \frac{S_t}{S_i} \quad (2\text{-}6)$$

Where $CLR_{e,t}$ = cumulative regional load reduction in year *t* for end-use *e* (TBtu or trillion lumen-hours)

$LR_{e,i}$ = regional load reduction in year *i* for end-use *e*

S_t = building stock in year *t*

S_i = building stock in year *i*.

For new buildings:

$$CLR_{e,t} = \sum_{i=1}^{t} LR_{e,i} \quad (2\text{-}7)$$

Where $CLR_{e,t}$ = cumulative regional load reduction in year *t* for end-use *e* (TBtu or trillion lumen-hours)

$LR_{e,i}$ = regional load reduction in year *i* for end-use *e*.

2.1.1.5 Calculate Energy Savings

The cumulative regional load reductions must be translated into regional energy savings, requiring baseline assumptions for existing equipment efficiencies and existing equipment market shares. Equipment efficiencies were developed based on EIA's *Annual Energy Outlook 2003 Supplemental Tables*. Equipment market shares are broken out by market segment and are estimated based on the 1997 "Residential Energy Consumption Survey" (EIA 1999), the 1999 "Commercial Buildings Energy Consumption Survey" (EIA 1999) and NEMS data files for 2003.

First, the cumulative regional load reductions are divided by the baseline equipment efficiencies, yielding potential energy savings by equipment type and end use. For envelope projects, this efficiency is the stock efficiency, or the efficiency of the existing installed base of equipment. Envelope projects do not replace any existing pieces of equipment, impacting only the building shell. In contrast, whole-building projects completely renovate a building and would likely impact newly replaced or installed equipment. Sales, or current-year, equipment efficiencies are used in this case. The potential energy savings assume that each equipment type has 100% of the market, so the actual equipment market shares must then be applied. The market share for each equipment type is multiplied by the potential energy savings to determine the actual energy savings. Equation 2-8 illustrates the energy savings by equipment type and end use calculations:

$$CES_{e,f,q,t} = \frac{CLR_{e,t}}{e_{e,f,q,t}} \times M_{e,f,q,t} \tag{2-8}$$

Where $CES_{e,f,q,t}$ = cumulative regional energy savings in year *t* for end-use *e*, fuel type *f*, and equipment type *q* (TBtu, or for lighting, billion kWh)

$CLR_{e,t}$ = cumulative regional load reduction in year *t* for end-use *e*

$e_{e,f,q,t}$ = equipment efficiency in year *t* for end-use *e*, fuel type *f*, and equipment type *q* (for lighting, this is lumens/watt, for other equipment this may be in terms of AFUE, COP, SCOP, or EF)

$M_{e,f,q,t}$ = market share in year *t* for end-use *e*, fuel type *f*, and equipment type *q*.

After converting lighting savings to TBtu, all calculated savings are aggregated by building sector, type, vintage, region, and fuel type to determine the total site electric savings, total natural gas savings, and total oil savings.

2.1.2 Equipment Project Approach

This section addresses projects that target equipment other than lighting. Equipment projects are characterized using new equipment efficiency.

Calculating the energy savings associated with an equipment project involves the following steps, which are discussed in the next subsections:

- Determine the size of the potential market and the number of units affected by the buildings-related project.
- Calculate adjustments to the potential market and units affected.
- Determine the base energy consumption of impacted units.
- Determine the energy consumption of impacted units after project implementation.
- Calculate the energy savings.

2.1.2.1 Determine Size of Potential Market and Number of Units Affected by the Buildings-Related Project

Estimates of building stock, base equipment market share and life, project equipment life, and penetration rates all play a role in determining the potential market and the number of units affected by equipment projects. Unlike the relatively straightforward calculations for the envelope and whole-building projects, equipment calculations are much more complicated. The primary driver behind this is the fact that equipment projects involve devices that fail within a shorter time-frame, relative to the envelope and whole-building projects, and must be replaced during the analysis period. Despite the additional level of complexity, the initial steps are similar.

Each equipment project has a specified target market—residential and/or commercial (and their subsets), new and/or existing vintages, and north and/or south regions.

For the initial calculation, the potential market for any equipment project is, for the targeted building set, the product of the equipment stock and the base equipment replacement factor. The equipment stock is derived through multiplication of the building stock and the equipment market shares. A replacement factor is calculated as the inverse of base equipment life, and indicates the frequency of required replacements. The derivations of equipment stock and the potential market are shown in Equations 2-9 and 2-10, respectively.

$$SE_{e,f,q,t} = S_t \times M_{e,f,q,t} \tag{2-9}$$

Where $SE_{e,f,q,t}$ = equipment stock in year *t* for end-use *e*, fuel type *f*, and equipment type *q* (billions ft^2 or million households)
S_t = building stock in year *t* (billion ft^2 or million households)
$M_{e,f,q,t}$ = equipment market share in year *t* for end-use *e*, fuel type *f*, and equipment type *q*.

$$PM_{e,f,q,t} = SE_{e,f,q,t} \times \frac{1}{BLife_{e,f,q}} = SE_{e,f,q,t} \times BR_{e,f,q} \tag{2-10}$$

Where $PM_{e,f,q,t}$ = potential market in year *t* for end-use *e*, fuel type *f*, and equipment type *q* (billion ft^2 or million households)
$SE_{e,f,q,t}$ = equipment stock in year *t* for end-use *e*, fuel type *f*, and equipment type *q* (billion ft^2 or million households)
$BLife_{e,f,q}$ = base equipment life expectancy for end-use *e*, fuel type *f*, and equipment type *q* (years)
$BR_{e,f,q}$ = base equipment replacement factor for end-use *e*, fuel type *f*, and equipment type *q*.

To initially calculate the number of units affected by the buildings-related project, the penetration rate, or fraction of sales, is applied to the potential market, as follows:

$$u_{e,f,q,nf,t} = P_{e,f,q,nf,t} \times PM_{e,f,q,t} \tag{2-11}$$

Where $u_{e,f,q,nf,t}$ = number of units affected in year *t* for end-use *e*, existing fuel type *f*, equipment type *q*, and new fuel *nf* (billion ft^2 or million households)

$P_{e,f,q,nf,t}$ = penetration rate in year *t* for end-use *e*, existing fuel type *f*, equipment type *q*, and new fuel *nf* (provided in the project characterization)

$PM_{e,f,q,t}$ = potential market in year *t* for end-use *e*, fuel type *f*, and equipment type *q* (billion ft^2 or million households).

In reality, *f* sufficiently represents the various possible fuel types. However, to illuminate the significant probability of fuel switching under equipment projects, *nf* is used here to represent the fuel type of project-installed equipment. Where there is no fuel switching, $nf = f$.

In contrast to the case for envelope and whole-building projects, the basic units calculation for equipment illustrated here does not require any special handling of existing buildings. With envelope and whole-building projects, penetration occurs against the entire building stock. For equipment projects, penetration occurs against only a portion of the building stock because of the use of a replacement factor. As a result, the existing vintage cumulative problem described in the envelope and whole-building approach does not exist here.

2.1.2.2 Calculate Adjustments to Potential Market and Units Affected

While this initial calculation of potential market and impacted units outlined above is fairly simple, the following steps are much more involved. Because base equipment life and project equipment life may differ, a project installation (unit impacted) in year *t* may impact the potential market in future years, which in turn affects project installations in future years. Handling this issue requires an iterative process. The results of the calculations of the previous section serve as inputs to this process.

The issue of differing base and project-sponsored equipment lives is not the only complicating factor. The annual (rather than cumulative) nature of new building stock numbers requires unique coding to ensure recompetition of new vintage installations upon failure. This treatment renders new vintage handling consistent with that for existing buildings. Without this added treatment, new vintage installations (whether base equipment or project equipment) would always be replaced with like equipment upon failure, ignoring a valid possibility of additional project penetration.

Beginning with the existing vintage case for the potential market, the calculations of this iterative updating process are outlined below as a series of conditional statements:

$$
\begin{aligned}
&PM_{e,f,q,t} = \\
&\left(If\,(t\text{-}1) \geq BLife_{e,f,q}\ then\ \frac{PM_{e,f,q,(t\text{-}BLife_{e,f,q})}}{SE_{e,f,q,(t-BLife_{e,f,q})}} \times SE_{e,f,q,t},\ else\ PM_{e,f,q,t} \right) \\
&- \left(If\,(t\text{-}1) \geq BLife_{e,f,q}\ then\ \frac{u_{e,f,q,nf,(t\text{-}BLife_{e,f,q})}}{SE_{e,f,q,(t\text{-}BLife_{e,f,q})}} \times SE_{e,f,q,t},\ else\ 0 \right) \\
&+ \left(If\,(t\text{-}1) \geq PLife_{e,f,q}\ then\ \frac{u_{e,f,q,nf,(t\text{-}PLife_{e,f,q})}}{SE_{e,f,q,(t\text{-}PLife_{e,f,q})}} \times SE_{e,f,q,t},\ else\ 0 \right)
\end{aligned}
\tag{2-12}
$$

Where $PM_{e,f,q,t}$ = potential market in year *t* for end-use *e*, fuel type *f*, and equipment type *q*
$BLife_{e,f,q}$ = base equipment life expectancy for end-use *e*, fuel type *f*, and equipment type *q* (years)
$PLife_{e,f,q}$ = project equipment life expectancy for end-use *e*, fuel type *f*, and equipment type *q* (years)
$SE_{e,f,q,t}$ = equipment stock in year *t* for end-use *e*, fuel type *f*, and equipment type *q*
$u_{e,f,q,nf,t}$ = number of units affected in year *t* for end-use *e*, existing fuel type *f*, equipment type *q*, and new fuel *nf*.

.

For new buildings:

$$
\begin{aligned}
PM_{e,f,q,t} &= \left(SE_{e,f,q,t}\right) + \left(If\,(t\text{-}1) \geq BLife_{e,f,q}\ then\ PM_{e,f,q,(t-BLife_{e,f,q})} \times \left(1\text{-}P_{e,f,q,nf,(t\text{-}BLife_{e,f,q})}\right),\ else\ 0 \right) \\
&+ \left(If\,(t\text{-}1) \geq PLife_{e,f,q}\ then\ u_{e,f,q,nf,(t-PLife_{e,f,q})},\ else\ 0 \right)
\end{aligned}
\tag{2-13}
$$

Where $PM_{e,f,q,t}$ = potential market in year *t* for end-use *e*, fuel type *f*, and equipment type *q*
$BLife_{e,f,q}$ = base equipment life expectancy for end-use *e*, fuel type *f*, and equipment type *q* (years)
$PLife_{e,f,q}$ = project equipment life expectancy for end-use *e*, fuel type *f*, and equipment type *q* (years)
$SE_{e,f,q,t}$ = equipment stock in year *t* for end-use *e*, fuel type *f*, and equipment type *q*
$P_{e,f,q,nf,t}$ = penetration rate in year *t* for end-use *e*, existing fuel type *f*, equipment type *q*, and new fuel *nf*
$u_{e,f,q,nf,t}$ = number of units affected in year *t* for end-use *e*, existing fuel type *f*, equipment type *q*, and new fuel *nf*.

These calculations are carried out for all years sequentially for each market segment, beginning with the first year. After the potential market is recalculated for a given year, the impacted units for that year must be recalculated, using Equation 2-11.

2.1.2.3 Determine Base Energy Consumption of Impacted Units

Building-level base energy consumption is calculated by dividing end-use loads by base equipment efficiencies. These efficiencies represent the sales, or current-year, efficiencies of equipment that would be installed absent a buildings-related project. End-use loads represent the baseline service requirements per square foot (commercial) or per household (residential) for heating, cooling, and water heating. As such, they must be divided by an efficiency to determine energy consumption:

$$bc_{e,f,q,t} = \frac{L_{e,t}}{e_{e,f,q,t}} \tag{2-14}$$

Where $bc_{e,f,q,t}$ = building-level base consumption in year *t* for end-use *e*, fuel type *f*, and equipment type *q* (kBtu/ft^2 or MMBtu/household)

$L_{e,t}$ = end-use load in year *t* for end-use *e* (kBtu/ft^2 or MMBtu/household)

$e_{e,f,q,t}$ = base equipment efficiency in year *t* for end-use *e*, fuel type *f*, and equipment type *q* (AFUE, COP, SCOP, or EF).

Multiplying this result by the number of impacted units yields regional base consumption:

$$BC_{e,f,q,t} = bc_{e,f,q,t} \times u_{e,f,q,t} \tag{2-15}$$

Where $BC_{e,f,q,t}$ = regional base consumption of impacted units in year *t* for end-use *e*, fuel type *f*, and equipment type *q* (TBtu)

$bc_{e,f,q,t}$ = building-level base consumption in year *t* for end-use *e*, fuel type *f*, and equipment type *q* (kBtu/ft^2 or MMBtu/household)

$u_{e,f,q,t}$ = total number of units impacted in year *t* for end-use *e*, fuel type *f*, and equipment type *q* (billion ft^2 or million households).

Because the final goal is calculating energy savings associated with impacted units, deriving total base consumption is not necessary; rather base consumption associated with impacted units only suffices.

At this point, the consumption figures are cumulated across years of the analysis. Each piece of equipment continues to consume energy throughout its lifetime. Therefore, in a given year, consumption may result from equipment installed in several previous years as well. The calculations, as shown in the equations below, provide aggregate energy consumption in each year, while taking into account the effect of declining building stock for existing buildings. This declining building stock acts to reduce consumption somewhat over time. To compare the base and project equipment's energy usage appropriately, the base consumption is cumulated over the lifetime of the project equipment. For existing buildings:

$$CBC_{e,f,q,t} = \sum_{i=(t-PLife_{e,f,q})}^{t} BC_{e,f,q,i} \times \frac{S_t}{S_i}, \text{ for } t > \text{PLife} \tag{2-16}$$

$$CBC_{e,f,q,t} = \sum_{i=1}^{t} BC_{e,f,q,i} * \frac{S_t}{S_i}, \text{ for } t \leq \text{PLife} \quad (2\text{-}17)$$

Where $CBC_{e,f,q,t}$ = cumulative regional base energy consumption in year *t* for end-use *e*, fuel type *f*, and equipment type *q* (TBtu)

$BC_{e,f,q,i}$ = regional base energy consumption in year *i* for end-use *e*, fuel type *f*, and equipment type *q*

S_t = building stock in year *t*

S_i = building stock in year *i*

$PLife_{e,f,q}$ = project equipment life expectancy for end-use *e*, fuel type *f*, and equipment type *q* (years).

For new buildings:

$$CBC_{e,f,q,t} = \sum_{i=(t-PLife_{e,f,q})}^{t} BC_{e,f,q,i}, \text{ for } t > \text{PLife} \quad (2\text{-}18)$$

$$CBC_{e,f,q,t} = \sum_{i=1}^{t} BC_{e,f,q,i}, \text{ for } t \leq \text{PLife} \quad (2\text{-}19)$$

Where $CBC_{e,f,q,t}$ = cumulative regional base energy consumption in year *t* for end-use *e*, fuel type *f*, and equipment type *q* (TBtu)

$BC_{e,f,q,i}$ = regional base energy consumption in year *i* for end-use *e*, fuel type *f*, and equipment type *q*

$PLife_{e,f,q}$ = project equipment life expectancy for end-use *e*, fuel type *f*, and equipment type *q* (years).

2.1.2.4 Determine Energy Consumption of Impacted Units After Project Implementation

The performance inputs for equipment projects are defined in terms of new equipment efficiencies. A directly parallel process to that described in the previous section (Determine Base Energy Consumption of Impacted Units) is used to calculate consumption associated with the project equipment. In this case, the initial step uses the performance inputs for the project equipment, rather than the base equipment efficiency:

$$pc_{e,nf,q,t} = \frac{L_{e,t}}{p_{e,nf,q,t}} \quad (2\text{-}20)$$

Where $pc_{e,nf,q,t}$ = building-level project consumption in year *t* for end-use *e*, new fuel *nf*, and equipment type *q* (kBtu/ft^2 or MMBtu/household)

$L_{e,t}$ = load in year *t* for end-use *e* (kBtu/ft^2 or MMBtu/household)

$p_{e,nf,q,t}$ = project equipment efficiency in year *t* for end-use *e*, new fuel *nf*, and equipment type *q* (AFUE, COP, SCOP, or EF).

All other steps toward deriving cumulative regional project energy consumption, CPC, are identical to those described in the previous section.

2.1.2.5 Calculate Energy Savings

With equipment projects, a significant probability of fuel switching exists. To calculate energy savings where the base fuel type is the same as the buildings-related project fuel type, project consumption is subtracted from base consumption:

$$CES_{e,f,q,t} = CBC_{e,f,q,t} - CPC_{e,nf,q,t} \tag{2-21}$$

Base fuel savings where the base fuel type is different from the project fuel type are simply the entire base fuel use:

$$CES_{e,f,q,t} = CBC_{e,f,q,t} \tag{2-22}$$

Project fuel savings where the base fuel type is different from the project fuel type are recorded as the negative of project consumption:

$$CES_{e,nf,q,t} = -CPC_{e,nf,q,t} \tag{2-23}$$

Where $CES_{e,f,q,t}$ = cumulative regional energy savings in year *t* for end-use *e*, fuel type *f*, and equipment type *q* (TBtu)

$CBC_{e,f,q,t}$ = cumulative regional base energy consumption in year *t* for end-use *e*, fuel type *f*, and equipment type *q* (TBtu)

$CPC_{e,nf,q,t}$ = cumulative regional project energy consumption in year *t* for end-use *e*, new fuel *nf*, and equipment type *q* (TBtu).

These savings (with some being negative) are combined and summed over end uses and equipment to provide the final net energy savings. The final net energy savings are aggregated by building sector, type, vintage, region, and fuel type to determine the total site electric savings, total natural gas savings, and total oil savings.

2.1.3 Lighting Project Approach

This section addresses projects targeting lighting that are modeled using BEAMS. Lighting projects are characterized by a change in the measure of light output per unit of power, or lumens per watt.

Calculating the energy savings associated with a lighting project involves the following steps, which are discussed in the next subsections:

- Determine the size of the potential market and the number of units affected by the buildings-related project.
- Calculate adjustments to the potential market and units affected.
- Determine the base energy consumption of impacted units.
- Determine the energy consumption of impacted units after project implementation.
- Calculate the lighting energy savings.

- Calculate the heating and cooling interactive effects factors.
- Calculate the change in space conditioning energy use due to interactive effects.
- Derive the final energy savings.

2.1.3.1 Determine Size of Potential Market and Number of Units Affected by the Buildings-Related Project

Unlike envelope and whole-building projects, lighting projects involve equipment that fails and must be replaced during the analysis period. Despite this additional level of complexity, the initial steps are similar.

Each lighting project has a specified target market: residential and/or commercial (and their subsets), new and/or existing vintages, and north and/or south regions.

For the initial calculation, the potential market for any lighting project is, for the targeted building set, the product of the equipment stock and the base equipment replacement factor. The equipment stock is derived by multiplying the building stock and the equipment market shares. A replacement factor is calculated as the inverse of base equipment life and indicates the frequency of required replacements. The derivations of equipment stock and the potential market are shown in Equations 2-24 and 2-25, respectively.

$$SE_{e,f,q,t} = S_t \times M_{e,f,q,t} \tag{2-24}$$

Where $SE_{e,f,q,t}$ = equipment stock in year *t* for end-use *e*, fuel type *f*, and equipment type *q* (billion ft^2 or million households)
S_t = building stock in year *t* (billion ft^2 or million households)
$M_{e,f,q,t}$ = equipment market share in year *t* for end-use *e*, fuel type *f*, and equipment type *q*.

$$PM_{e,f,q,t} = SE_{e,f,q,t} \times \frac{1}{BLife_{e,f,q}} = SE_{e,f,q,t} \times BR_{e,f,q} \tag{2-25}$$

Where $PM_{e,f,q,t}$ = potential market in year *t* for end-use *e*, fuel type *f*, and equipment type *q* (billion ft^2 or million households)
$SE_{e,f,q,t}$ = equipment stock in year *t* for end-use *e*, fuel type *f*, and equipment type *q* (billion ft^2 or million households)
$BLife_{e,f,q}$ = base equipment life expectancy for end-use *e*, fuel type *f*, and equipment type *q* (years)
$BR_{e,f,q}$ = base equipment replacement factor for end-use *e*, fuel type *f*, and equipment type *q*.

To initially calculate the number of units affected by the BT/WIP project, the penetration rate, or fraction of sales, is applied to the potential market, as follows:

$$u_{e,f,q,t} = P_{e,f,q,t} \times PM_{e,f,q,t} \tag{2-26}$$

Where $u_{e,f,q,t}$ = number of units affected in year *t* for end-use *e*, fuel type *f*, and equipment type *q* (billion ft^2 or million households)

$P_{e,f,q,t}$ = penetration rate in year *t* for end-use *e*, fuel type *f*, and equipment type *q* (provided in the project characterization)

$PM_{e,f,q,t}$ = potential market in year *t* for end-use *e*, fuel type *f*, and equipment type *q* (billion ft^2 or million households).

In contrast to envelope and whole-building projects, the basic units calculation for lighting illustrated here does not require any special handling of existing buildings. With envelope and whole-building projects, penetration occurs against the entire building stock. For lighting, penetration occurs against only a portion of the building stock because a replacement factor is used. As a result, the existing vintage cumulative problem described in the envelope and whole-building approach does not exist here.

2.1.3.2 Calculate Adjustments to the Potential Market and Units Affected

While this initial calculation of potential market and impacted units outlined above is fairly simple, the following steps are much more involved. Because base equipment life and project equipment life may differ (e.g., lives of CFLs and incandescents), a project installation (unit impacted) in year *t* may impact the potential market in future years, which in turn affects project installations in future years. Handling this issue requires an iterative process. The results of the calculations of the previous section serve as inputs to this process.

The issue of differing base and buildings-related project lives is not the only complicating factor. The annual (rather than cumulative) nature of new building stock numbers requires unique coding to ensure recompetition of new vintage installations upon failure. This treatment renders new vintage handling consistent with that for existing buildings. Without this added treatment, new vintage installations (whether base equipment or project equipment) would always be replaced with like equipment upon failure, ignoring a valid possibility of additional project penetration.

Beginning with the existing vintage case for the potential market, the calculations of this iterative updating process are outlined below as a series of conditional statements:

$$
\begin{aligned}
&PM_{e,f,q,t} = \\
&\left(If\,(t\text{-}1) \geq BLife_{e,f,q}\ then\ \frac{PM_{e,f,q,(t\text{-}BLife_{e,f,q})}}{SE_{e,f,q,(t-BLife_{e,f,q})}} \times SE_{e,f,q,t},\ else\ PM_{e,f,q,t} \right) \\
&- \left(If\,(t\text{-}1) \geq BLife_{e,f,q}\ then\ \frac{u_{e,f,q,(t\text{-}BLife_{e,f,q})}}{SE_{e,f,q,(t\text{-}BLife_{e,f,q})}} \times SE_{e,f,q,t},\ else\ 0 \right) \\
&+ \left(If\,(t\text{-}1) \geq PLife_{e,f,q}\ then\ \frac{u_{e,f,q,(t\text{-}PLife_{e,f,q})}}{SE_{e,f,q,(t\text{-}PLife_{e,f,q})}} \times SE_{e,f,q,t},\ else\ 0 \right)
\end{aligned}
\tag{2-27}
$$

Where $PM_{e,f,q,t}$ = potential market in year *t* for end-use *e*, fuel type *f*, and equipment type *q*

$BLife_{e,f,q}$	=	base equipment life expectancy for end-use *e*, fuel type *f*, and equipment type *q* (years)
$PLife_{e,f,q}$	=	project equipment life expectancy for end-use *e*, fuel type *f*, and equipment type *q* (years)
$SE_{e,f,q,t}$	=	equipment stock in year *t* for end-use *e*, fuel type *f*, and equipment type *q*
$u_{e,f,q,t}$	=	number of units affected in year *t* for end-use *e*, fuel type *f*, and equipment type *q*.

For new buildings:

$$PM_{e,f,q,t} = \left(SE_{e,f,q,t}\right) + \left(If\ (t\text{-}1) \geq BLife_{e,f,q}\ then\ PM_{e,f,q,(t-BLife_{e,f,q})} \times \left(1\text{-}P_{e,f,q,(t\text{-}BLife_{e,f,q})}\right), else\ 0\right) + \left(If\ (t\text{-}1) \geq PLife_{e,f,q}\ then\ u_{e,f,q,(t-PLife_{e,f,q})}, else\ 0\right) \quad (2\text{-}28)$$

Where

$PM_{e,f,q,t}$	=	potential market in year *t* for end-use *e*, fuel type *f*, and equipment type *q*
$BLife_{e,f,q}$	=	base equipment life expectancy for end-use *e*, fuel type *f*, and equipment type *q* (years)
$PLife_{e,f,q}$	=	project equipment life expectancy for end-use *e*, fuel type *f*, and equipment type *q* (years)
$SE_{e,f,q,t}$	=	equipment stock in year *t* for end-use *e*, fuel type *f*, and equipment type *q*
$P_{e,f,q,t}$	=	penetration rate in year *t* for end-use *e*, fuel type *f*, and equipment type *q*
$u_{e,f,q,t}$	=	number of units affected in year *t* for end-use *e*, fuel type *f*, and equipment type *q*.

These calculations are carried out for all years sequentially for each market segment, beginning with the first year. After the potential market is recalculated for a given year, the impacted units for that year must be recalculated, using Equation 2-26 above.

2.1.3.3 Determine Base Energy Consumption of Impacted Units

Building-level base energy consumption is calculated by dividing end-use loads by base equipment efficiencies. These efficiencies represent the sales, or current-year, efficiencies of equipment that would be installed absent a buildings-related project. End-use loads represent the baseline service requirements per square foot (commercial) or per household (residential) for lighting. As such, they must be divided by an efficiency to determine energy consumption:

$$bc_{e,f,q,t} = \frac{L_{e,t}}{e_{e,f,q,t}} \quad (2\text{-}29)$$

Where

$bc_{e,f,q,t}$	=	building-level base consumption in year *t* for end-use *e*, fuel type *f*, and equipment type *q* (kWh/ft^2 or MWh/household)
$L_{e,t}$	=	end-use load in year *t* for end-use *e* (thousand lumen-hours/ft^2 or million lumen-hours/household)
$e_{e,f,q,t}$	=	base equipment efficiency in year *t* for end-use *e*, fuel type *f*, and equipment type *q* (lumens/watt).

Multiplying this result by the number of impacted units yields regional base consumption:

$$BC_{e,f,q,t} = bc_{e,f,q,t} \times u_{e,f,q,t} \tag{2-30}$$

Where $BC_{e,f,q,t}$ = regional base consumption of impacted units in year *t* for end-use *e*, fuel type *f*, and equipment type *q* (billion kWh)

$bc_{e,f,q,t}$ = building-level base consumption in year *t* for end-use *e*, fuel type *f*, and equipment type *q* (kWh/ft^2 or MWh/household)

$u_{e,f,q,t}$ = total number of units impacted in year *t* for end-use *e*, fuel type *f*, and equipment type *q* (billion ft^2 or million households).

This result is converted from billion kWh to TBtu, using a standard conversion of 3412 BTU/kWh.

Because the final goal is to calculate energy savings associated with impacted units, deriving total base consumption is not necessary; rather base consumption associated with impacted units only suffices.

At this point, the consumption figures are cumulated across years of the analysis. Each piece of equipment continues to consume energy throughout its lifetime. Therefore, in a given year, consumption may result from equipment installed in several previous years as well. The calculations, as shown in the equations below, provide aggregate energy consumption in each year, while taking into account the effect of declining building stock for existing buildings. This declining building stock acts to reduce consumption somewhat over time. To compare the base and project equipment's energy usage appropriately, the base consumption is cumulated over the lifetime of the project equipment. For existing buildings:

$$CBC_{e,f,q,t} = \sum_{i=(t-PLife_{e,f,q})}^{t} BC_{e,f,q,i} \times \frac{S_t}{S_i}, \text{ for t > PLife} \tag{2-31}$$

$$CBC_{e,f,q,t} = \sum_{i=1}^{t} BC_{e,f,q,i} \times \frac{S_t}{S_i}, \text{ for t} \leq \text{PLife} \tag{2-32}$$

Where $CBC_{e,f,q,t}$ = cumulative regional base energy consumption in year *t* for end-use *e*, fuel type *f*, and equipment type *q* (TBtu)

$BC_{e,f,q,i}$ = regional base energy consumption in year *i* for end-use *e*, fuel type *f*, and equipment type *q*

S_t = building stock in year *t*

S_i = building stock in year *i*

$PLife_{e,f,q}$ = project equipment life expectancy for end-use *e*, fuel type *f*, and equipment type *q* (years).

For new buildings:

$$CBC_{e,f,q,t} = \sum_{i=(t-PLife_{e,f,q})}^{t} BC_{e,f,q,i}, \text{ for t > PLife} \tag{2-33}$$

$$CBC_{e,f,q,t} = \sum_{i=1}^{t} BC_{e,f,q,i}, \text{ for } t \leq \text{PLife} \quad (2\text{-}34)$$

Where $CBC_{e,f,q,t}$ = cumulative regional base energy consumption in year *t* for end-use *e*, fuel type *f*, and equipment type *q* (TBtu)

$BC_{e,f,q,i}$ = regional base energy consumption in year *i* for end-use *e*, fuel type *f*, and equipment type *q*

$PLife_{e,f,q}$ = project equipment life expectancy for end-use *e*, fuel type *f*, and equipment type *q* (years).

2.1.3.4 Determine Energy Consumption of Impacted Units After Project Implementation

The performance inputs for lighting projects are defined in terms of new equipment efficiencies. A directly parallel process to that described in the previous section (Determine Base Energy Consumption of Impacted Units) is used to calculate consumption associated with the project equipment. In this case, the initial step uses the performance inputs for the project equipment, rather than the base equipment efficiency:

$$pc_{e,f,q,t} = \frac{L_{e,t}}{p_{e,f,q,t}} \quad (2\text{-}35)$$

Where $pc_{e,f,q,t}$ = building-level project consumption in year *t* for end-use *e*, fuel *f*, and equipment type *q* (kWh/ft^2 or MWh/household)

$L_{e,t}$ = load in year *t* for end-use *e* (thousand lumen-hours/ft^2 or million lumen-hours/household)

$p_{e,f,q,t}$ = project equipment efficiency in year *t* for end-use *e*, fuel *f*, and equipment type *q* (lumens/watt).

All other steps toward deriving cumulative regional project energy consumption, CPC, are identical to those described in the previous section.

2.1.3.5 Calculate Lighting Energy Savings

Unlike equipment projects, where a significant probability of fuel switching exists, the lighting case is more straightforward. To calculate lighting energy savings, project consumption is subtracted from base consumption:

$$CES_{e,f,q,t} = CBC_{e,f,q,t} - CPC_{e,f,q,t} \quad (2\text{-}36)$$

Where $CES_{e,f,q,t}$ = cumulative regional energy savings in year *t* for end-use *e*, fuel type *f*, and equipment type *q* (TBtu)

$CBC_{e,f,q,t}$ = cumulative regional base energy consumption in year *t* for end-use *e*, fuel type *f*, and equipment type *q* (TBtu)

$CPC_{e,f,q,t}$ = cumulative regional project energy consumption in year *t* for end-use *e*, fuel *f*, and equipment type *q* (TBtu).

2.1.3.6 Calculate Heating and Cooling Interactive Effects Factors

A change in lighting consumption significantly impacts other end uses as well. As more efficient lighting is incorporated in buildings, heating loads can be expected to increase, while cooling loads should be reduced. These interactions are accounted for through the development and use of lighting interaction factors. BEAMS incorporates interactive effects coefficients as inputs, which are used to derive heating and cooling load change factors.

2.1.3.6.1 Derivation of the interactive effects coefficients—Baseline

Baseline loads were determined using NEMSFEDS, an iteration tool based on FEDS that allows a single case to be modified and run (loads only) by altering inputs to a [casename].ini file. In this manner a single case can be used to run a multi-dimensional matrix of all combinations of building type, size, vintage, location, occupancy, and lighting configurations. Statistical data of actual building size and vintage information were then used to combine the NEMSFEDS results into a location by building type results matrix where each building type is of the weighted average size and weighted average vintage (for existing) or 2000 vintage for new buildings.

Values were determined for all combinations of the following:

- Commercial, residential, and industrial building types
- New and existing buildings
- Nine census regions (and north and south for BEAMS).

2.1.3.6.2 Derivation of the interactive effects coefficients—Variation from Baseline

Lighting consumption was decreased from 100% to 0% with 10% steps. As a result of the decrease in lighting consumption, the heating load increased and the cooling load decreased. The fractional increases in the heating load and fractional decreases in the cooling load were then determined at each of the steps. Lastly, the results were converted via regression to equations (one for heat and one for cooling for each combination of building type, new/existing, and location) where the only input is the percentage reduction in the lighting consumption. The regression equations are of the form:

$$\Delta heat = a \times \Delta L^{b} \tag{2-37}$$

$$\Delta cool = c \times \Delta L^{2} + d \times \Delta L \tag{2-38}$$

Where *a, b, c*, and *d* are the interactive effects coefficients

Δheat = the fractional change in heating load

Δcool = the fractional change in cooling load

ΔL = the percentage reduction in lighting consumption.

2.1.3.6.3 Specification

Because of the way this was modeled the implicit assumption is that a 20% penetration rate means that 20% of the lighting within all buildings of a certain type, vintage, and region get the buildings-related technology. Hence the 20% value can be used directly. The alternative, which could also be easily modeled using the data generated in this activity, is that 20% of the buildings within a certain type, vintage, and region have 100% of the buildings-related technology. This would require that a weighted average be developed (20% with 100% penetration and 80% with 0% penetration).

2.1.3.6.4 Calculation of Interactive Effects Factors

To calculate the necessary input, ΔL, the previously calculated cumulative regional base consumption and energy savings are first aggregated across equipment types, as the lighting source does not affect the interactive effects. The percentage reduction in lighting consumption is calculated as:

$$\Delta L = \left(\frac{CES_t}{CBC_t} \right) \times 100 \qquad (2\text{-}39)$$

Where ΔL = the percentage reduction in lighting consumption
CES_t = cumulative regional lighting energy savings in year *t* (TBtu)
CBC_t = cumulative regional base lighting consumption in year *t* (TBtu).

At this point, the required components for calculating the interactive effects factors are available. Using Equations 2-37 and 2-38, Δheat and Δcool are computed.

2.1.3.7 Calculate Change in Space Conditioning Energy Use Due to Interactive Effects

The load changes from interactive effects are calculated by applying the interactive effects factors to the cumulative regional lighting energy savings (calculated previously in equations 2-36). As noted earlier, as lighting efficiency increases, cooling loads decrease and heating loads increase. As a result, the calculated values for Δheat are positive, and those for Δcool are negative. Because the load reduction, rather than the change in load, is the desired output, a sign change is applied in the following calculation:

For heating:

$$ILR_{e,f,q,t} = CES_{e,f,q,t} \times (-\Delta heat) \qquad (2\text{-}40)$$

For cooling:

$$ILR_{e,f,q,t} = CES_{e,f,q,t} \times (-\Delta cool) \qquad (2\text{-}41)$$

Where $ILR_{e,f,q,t}$ = load reductions in year *t* due to interactive effects for end-use *e*, fuel type *f*, and equipment type *q* (TBtu)

$CES_{e,f,q,t}$ = cumulative regional energy savings for end-use *e*, fuel type *f*, and equipment type *q* (TBtu)
$\Delta heat$ = the fractional change in heating load
$\Delta cool$ = the fractional change in cooling load.

These load reductions must be translated into energy savings. To do this, baseline assumptions regarding existing equipment efficiencies and existing equipment market shares are used. First, the load reductions resulting from interactive effects are divided by the baseline existing equipment efficiencies, which yields potential energy savings by equipment type and end use. The potential energy savings assume that each equipment type has 100% of the market, so the actual equipment market shares must then be applied. The market share for each equipment type is multiplied by the potential energy savings to determine the actual energy savings. Equation 2-42 illustrates the energy savings by equipment type and end use calculations:

$$IES_{e,f,q,t} = \frac{ILR_{e,f,q,t}}{e_{e,f,q,t}} \times M_{e,f,q,t} \tag{2-42}$$

Where $IES_{e,f,q,t}$ = energy savings in year *t* due to interactive effects for end-use *e*, fuel type *f*, and equipment type *q* (TBtu)
$ILR_{e,f,q,t}$ = load reductions in year *t* due to interactive effects for end-use *e*, fuel type *f*, and equipment type *q* (TBtu)
$e_{e,f,q,t}$ = equipment efficiency in year *t* for end-use *e*, fuel type *f*, and equipment type *q* (AFUE, COP, or SCOP)
$M_{e,f,q,t}$ = equipment market share in year *t* for end-use *e*, fuel type *f*, and equipment type *q*.

2.1.3.8 Derive Final Energy Savings

The lighting energy savings and the space-conditioning energy savings are combined and summed over end uses and equipment to provide the final net energy savings. The final net energy savings are aggregated by building sector, type, vintage, region, and fuel type to determine the total site electric savings, total natural gas savings, and total oil savings.

2.1.4 Other Components

This section addresses calculations made within BEAMS that occur after the individual energy algorithms described above. Each of the following computations applies not only to BEAMS-estimated projects but also to projects with savings estimated by NEMS-PNNL or spreadsheets models. For projects estimated by methods other than BEAMS, site energy savings (electric, gas, and oil), investment, and any non-energy costs are first imported into BEAMS. These inputs are broken out by building sector, type, vintage, region, and year, as are all final outputs of the calculations described below.

2.1.4.1 Calculate Primary Energy Savings

For BEAMS-estimated projects, site energy savings are calculated within the algorithms already discussed above. For other projects, site energy savings are provided to BEAMS as an input. Total site energy consists of site electric, natural gas, and fuel oil savings. To derive primary electric savings, the external site electricity savings are multiplied by a year-specific electricity conversion factor within BEAMS. Primary non-electric savings consists of the sum of natural gas and oil savings. Summation of primary electricity and primary non-electric savings yields the total net primary energy savings. The units for all of these data are TBtu.

2.1.4.2 Calculate Emissions Reductions and Energy Cost Savings

BEAMS input data include energy prices and site-energy emission factors, both of which are building sector-, fuel- (electric, gas, and oil), and year-specific. Emission factors are included for carbon equivalent emissions, sulfur dioxide, nitrous oxides, volatile organic compounds, particulate matter, and carbon monoxide. EERE's GPRA guidance provided the various factors used ((Draft letter, Office of Energy Efficiency and Renewable Energy. April 1, 2002. "Performance Planning Guidance (GPRA Data Call) FY 2004-FY 2008 Budget Cycle." US Department of Energy, Washington, D.C.). Factors are multiplied by site energy savings, and prices are multiplied by the respective fuel savings. The resulting energy cost savings are reported in millions of dollars, and the emissions reductions are represented as millions of metric tons (MMton) avoided.

2.1.4.3 Determine Required Investment and Non-energy Costs

For projects estimated outside of BEAMS, investment and non-energy costs are provided as an input to BEAMS. For BEAMS-estimated projects, investment and non-energy costs are output as part of the process, and their estimation relies on the installed units calculated in the above algorithms. These units are in terms of either million households (residential), or billion square feet (commercial) building sectors. Per-unit equipment costs (dollars per square foot or dollars per household) are multiplied by installed units, as Equation 2-43 shows:

$$I_t = c_t \times u_t \qquad (2\text{-}43)$$

Where I_t = investment in year *t*
c_t = per-unit installed cost in year *t*
u_t = number of units impacted in year *t*.

Similarly, non-energy costs are calculated as follows:

$$NE_t = ne_t \times u_t \qquad (2\text{-}44)$$

Where NE_t = non-energy cost in year *t*
ne_t = per-unit non-energy cost in year *t*
u_t = number of units impacted in year *t*.

Each of these calculations is performed for base costs, project costs, and the incremental costs. After necessary conversions, the resulting investment and non-energy costs are reported in millions of dollars.

2.2 General Methodology Using NEMS-PNNL

Many of the buildings-related projects target specific types of equipment. Equipment projects are characterized by new equipment efficiencies and are compared with "baseline" efficiencies to calculate energy savings. To determine the penetration of the project-sponsored equipment relative to the more conventional equipment, a modified version of the NEMS model (NEMS-PNNL) employed for EIA's *Annual Energy Outlook* (EIA 1999) was used.

NEMS-PNNL selects specific technologies to meet the energy services demands by choosing among a discrete set of technologies that are externally characterized by commercial availability, capital costs, operating and maintenance costs, efficiencies, and lifetime. NEMS-PNNL is coded to allow several possible assumptions to be used about consumer behavior to model this selection process. For the GPRA effort, the menu of equipment was changed to include relevant project equipment, technological innovations, and standards.

The NEMS-PNNL design can accommodate various technology choices. For the GPRA effort, the NEMS-PNNL data input were adjusted to reflect DOE technology choices. For buildings-related projects that target efficiency of the building envelope (or shell), specific shell-efficiency indices were read into the model.

The NEMS-PNNL commercial and residential demand modules generate forecasts of energy demand (energy consumption) for the commercial and residential sectors. The commercial demand module generates fuel consumption forecasts for electricity, natural gas, and distillate fuel oil. These forecasts are based on energy prices and macroeconomic variables from the NEMS system, combined with external data sources. The residential model uses energy prices and macroeconomic indicators to generate energy consumption by fuel type and census division in the residential sector. The commercial and residential demand modules are described in the following subsections.

2.2.1 Commercial Demand

This module develops projects of energy consumption by major types of commercial buildings, including assembly, education, food service, food sales, health care, lodging, mercantile and service, office buildings, and warehouses. Commercial energy demand within NEMS-PNNL is calculated in four basic steps:

1. Forecast commercial sector floorspace.
2. Forecast energy services such as space conditioning equipment, lighting, water heating, and refrigeration.
3. Select specific technologies to meet the demand of energy services, which involves modeling consumer behavior and capturing the decision between such equipment as incandescent lights and fluorescent lights.
4. Determine how much energy will be consumed by the equipment chosen to meet the demand for energy services.

The third step is a key element in calculating the estimated energy savings of a given technology promoted by a particular buildings-related project. Within this step, consumers are assumed to purchase energy-using equipment to meet three types of service demands: services for new buildings, replacement of old equipment that is at the end of its technical life, and replacement of old equipment that is at the end of its economic life (although it still may be technically viable). The NEMS-PNNL commercial model is structured to allow the use of several possible assumptions about consumer behavior to model this decision process. The assumptions are designed to represent empirically the range of economic factors that most influence the consumer's decision and include the following:

- Consumer buys the equipment with the minimum life-cycle cost.
- Consumer buys equipment that uses the same fuel as existing and retiring equipment but minimizes costs across technologies using that fuel.
- Consumer buys (or keeps) the same technology as the existing and retiring equipment but chooses among different efficiency levels based on minimum life-cycle cost.

The model is designed to choose among a discrete set of technologies that are externally characterized by commercial availability, capital costs, operating and maintenance costs, efficiencies, and lifetime. For GPRA metrics, the menu of equipment may be altered to include relevant DOE project equipment, technological innovations, and standards. The NEMS-PNNL design can accommodate a changing menu of technology choices, recognizing that changes in energy prices and consumer demand may significantly change the set of relevant technologies that the model user wishes to consider.

2.2.2 Residential Demand

The residential sector demand module includes single-family, multifamily, and mobile home dwellings. Residential energy demand is modeled using a sequence of five steps:

1. Forecast housing stock.
2. Select the specific technologies to meet the demand for each energy service (e.g. furnaces and heat pumps).
3. Forecast appliance stocks that are required by each end-use service.
4. Forecast changes in building-shell integrity; building-shell efficiency in new construction is assumed to improve over the forecast period because of stricter building codes and other efficiency projects and may fluctuate in response to fuel price changes from the base year.
5. Calculate the energy consumed by the equipment chosen to meet the demand for energy services.

As with the commercial model, the GPRA metrics methodology involves modifying the technology performance and cost inputs to reflect the DOE project-developed equipment. The technology and equipment selection simulates the behavior of residential consumers based on the relative importance of life-cycle costs, capital costs, and operating costs of competing technologies within a service. Decisions on new and replacement equipment reflect additional factors beyond the traditional life-cycle cost methodology, including space heating fuel choice and previous equipment choices. The technology and equipment selection allocates end-use services based on a defined equipment menu of the various technologies and fuels that compete in the market.

2.2.3 Methodology for Market Transformation-Type Projects

This section discusses the methodological approach to calculating energy savings for projects that attempt to increase sales by modifying consumer behavior.

For a few appliances, some changes were made in the baseline assumptions made by EIA. The reasons for these changes are briefly discussed.

EIA labeled the two modeling parameters as Beta1 and Beta2. Beta1 is used as multiplicative factor with the initial cost of the appliance, and Beta2 is used to multiply the annual energy cost. The sum of the two products (i.e., Beta1 × initial cost + Beta2 × operating cost) is used in the logit specification to yield market shares for each technology. These coefficients are specific to each equipment type and fuel type. As a rough approximation, the ratio of Beta1/Beta2 can be interpreted as the consumer discount rate for the specific appliance. The Beta1 and Beta2 coefficients are contained with the cost and efficiency data inputs in the file RTEKTY. In the residential NEMS module, the Beta1 and Beta2 coefficients vary among appliances, as do the resulting discount rates. For example, the implied discount rate for refrigerators is 16%. On the other hand, the discount rate is estimated to be over 80% for electric water heaters.

2.2.4 Methodology for Equipment Projects

NEMS-PNNL was used to estimate the energy savings associated with equipment products being developed under buildings-related projects by modifying the NEMS-PNNL input files (RTEKTY.txt for residential, KTECH.wk1 for commercial) for each type of equipment.

For a few appliances, some changes were made in EIA's baseline assumptions. Where the original *Annual Energy Outlook* input file does not reflect pending standards that are scheduled to take effect during the analysis period, modifications were made to crudely account for these standards.

One issue related to assessing benefits with the NEMS-PNNL model is the appropriate discount rate to use. If the implied discount rate is too high, discouraging most consumers from choosing the technology, then the logit parameters, Beta1 and Beta2, may be modified. Energy Star or other market transformation projects provide impetus for increased market acceptance of selected technologies. Therefore, when appropriate, parameters are modified to decrease the implied discount rate (i.e., encourage consumers to choose this technology earlier) for the technologies targeted by these projects.

The project’s energy savings are therefore calculated as the difference between NEMS-PNNL model runs that 1) include the technology assumed in the *Annual Energy Outlook* base case and 2) substitute the lower-cost units assumed to stem from the buildings-related project.

2.2.5 GPRA Envelope Calculations Using NEMS-PNNL

The general approach for GPRA envelope calculations using NEMS-PNNL was to simulate the effect of an envelope technology using the FEDS model for many different building types, sizes, vintages, and locations. The heating and cooling loads were calculated for each building with and without the envelope technology being evaluated. The changes in the heating and cooling loads were then used to modify the heating and cooling envelope factors in NEMS-PNNL. These factors were input as a vector for each building type and census region; these vectors captured both the thermal impact and the expected market penetration by year. Market penetration estimates were based on input from the DOE project manager or their representatives.

2.2.5.1 FEDS Modeling

To estimate the national impact of introducing a new envelope technology, the impact of that technology must be accurately captured within the buildings where it is likely to be employed. For each technology, the impact was simulated in 3,960 commercial buildings and 1,188 residential buildings representing all combinations of building type, size, vintage, and location (see Table 2.1).

2.2.5.2 Aggregating FEDS Results for NEMS-PNNL

Because NEMS-PNNL only models one of each building type in each of the nine census regions, the FEDS results needed to be aggregated for input into NEMS-PNNL.

City Weights. The cities shown in Table 2.1 were selected for the FEDS analysis because the weather is characteristic of the climate in the different portions of the census regions. Because NEMS operates on a census region basis, weighted averages of the FEDS results for individual weather cities were produced to represent the loads within a census region. Table 2.2 shows the weights given to each city for each census region.

Table 2.1. Building Simulation Parameters

<table>
<tr><th>Building Type</th><th>Building Size (ft^2)</th><th>Vintage (Year Built)</th><th>Location</th></tr>
<tr><td>Assembly</td><td rowspan="10">4000
7500
17500
37500
75000
125000</td><td rowspan="13">1940
1953
1967
1976
1983
2000</td><td rowspan="13">Denver, Colorado
Detroit, Michigan
Fresno, California
Knoxville, Tennessee
Los Angeles, California
Minneapolis, Minnesota
Phoenix, Arizona
Providence, Rhode Island
Seattle, Washington
Shreveport, Louisiana
Tampa, Florida</td></tr>
<tr><td>Education</td></tr>
<tr><td>Food Sales</td></tr>
<tr><td>Food Service</td></tr>
<tr><td>Healthcare</td></tr>
<tr><td>Lodging</td></tr>
<tr><td>Mercantile and Service</td></tr>
<tr><td>Office</td></tr>
<tr><td>Warehouse</td></tr>
<tr><td>Other Commercial Buildings</td></tr>
<tr><td>Single Family</td><td rowspan="2">600
800
1300
1800
2200
3000*</td></tr>
<tr><td>Mobile Home</td></tr>
<tr><td>Multifamily</td><td>14309
19079
31003
42927
52466
71545</td></tr>
<tr><td colspan="4">*Single-family and mobile homes are represented by the 600 ft^2 to 3000 ft^2 single-family range.</td></tr>
</table>

Table 2.2. Weights Given to Each City for Each Census Region (%)

City	New England	Mid Atlantic	East North Central	West North Central	South Atlantic	East South Central	West South Central	Mountain	Pacific
Denver	0.0	0.0	0.0	0.0	0.0	0.0	0.0	64.0	2.2
Detroit	0.0	0.0	99.3	60.0	0.0	0.0	0.0	0.0	0.0
Fresno	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	13.3
Knoxville	0.0	0.0	0.0	0.0	50.7	67.4	13.4	0.0	0.0
Los Angeles	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	71.2
Minneapolis	0.0	0.0	0.7	40.0	0.0	0.0	0.0	0.0	0.0
Phoenix	0.0	0.0	0.0	0.0	0.0	0.0	0.0	36.0	0.0
Providence	100.0	100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Seattle	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	13.2
Shreveport	0.0	0.0	0.0	0.0	17.7	32.6	80.6	0.0	0.0
Tampa	0.0	0.0	0.0	0.0	31.6	0.0	6.0	0.0	0.0

Floor Area Weights. The fraction of floor space within each size category for each commercial building type was determined using data from 1995 "Commercial Buildings Energy Consumption Survey"[c] (EIA 1995) and is shown in Table 2.3.

Table 2.4 shows the fraction of floor space within each size category for each residential building type (single family, mobile homes, and multifamily). The data for single-family and mobile homes were determined using data from the 1997 "Residential Energy Consumption Survey"[d] (EIA 1997) and the data for multifamily homes were determined using data from survey and apartment stock data from the National Multi-Housing Council.[e]

Vintage Weights. For simplicity, all vintages were given equal weighting**.**

Market Penetration. The DOE project manager or representative provided market penetration point estimates. These estimates were then used in the previously developed and documented market penetration model (see Section 3.3, "Bass Diffusion Model") to estimate the market penetration by year.

[c] Table 9. Where no data were available, expert judgment was used.
[d] Table HC1-4b, single-family, and Table HC1-4b, five or more units.
[e] http://www.nmhc.org/content/ServeContent.cfm?IssueID=253&ContentItemId=141#size.

Table 2.3. Percentage of Floor Space in Each Size Category for Each Commercial Building Type (%)

Building Type	Floor Space Size Category—Range and [Modeled Size] ft^2						
	≤5,000 [4,000]	5,001-10,000 [7,500]	10,000-25,000 [17,500]	25,001-50,000 [37,500]	50,001-100,000 [75,000]	>100,000 [125,000]	Total
Assembly	7.9	19.9	23.8	12.3	12.6	23.5	100.0
Education	3.2	5.2	13.5	23.6	22.6	31.8	100.0
Food Sales	36.4	6.4	31.8	19.1	5.1	1.3	100.0
Food Service	40.7	28.8	24.4	5.2	0.6	0.3	100.0
Healthcare	6.5	6.5	10.4	7.5	5.5	63.6	100.0
Lodging	4.1	7.4	20.7	14.2	16.9	36.7	100.0
Mercantile and Service	14.5	17.3	23.1	9.3	10.0	25.7	100.0
Large Office	0.0	0.0	0.0	0.0	27.5	72.5	100.0
Small Office	21.7	18.9	32.7	26.7	0.0	0.0	100.0
Other Buildings	10.8	12.8	19.7	13.0	13.5	30.1	100.0
Warehouse	9.5	11.7	18.0	13.7	13.5	33.5	100.0

Table 2.4. Fraction of Floor Space in Each Size Category for Each Residential Type (%)

Building Type	Single-Family Residential Floor Space Size Category—Range and [Modeled Size] ft^2					
	≤600 [600]	601-999 [800]	1,000-1,599 [1,300]	1,600-1,999 [1,800]	2,000-2,399 [2,200]	>2,400 [3,000]
Single Family	2.8	14.0	37.0	21.2	11.3	13.7
Mobile Home	15.7	43.8	31.6	7.2	2.2	0.7
Building Type	**Multifamily Residential Floor Space Size Category—Range and [Modeled Size] ft^2**					
	≤14,309 [14,309]	**14,310-23,848 [19,079]**	**23,849-38157 [31,003]**	**38,158-47,696 [42,927]**	**47,697-57,236 [52,466]**	**>57,236 [71, 545]**
Multifamily	25.4	49.3	17.9	2.4	0.7	0.2

2.2.5.3 Baseline Assumptions

Consistent with the NEMS-PNNL model, the heating and cooling envelope factors were assumed to be decreasing over time. These changes account for technological improvements over time that would occur without the DOE project. The baseline envelope factors in NEMS-PNNL were modified annually to account for the technological improvements, and the modifiers are calculated using the following equation with 1995 being the base year:

$$BaselineModifier_{new\ buildings} = 0.94\left(\frac{Current\ Year - 1995}{25}\right)$$

(2-45)

$$BaselineModifier_{existing\ buildings} = 0.96\left(\frac{Current\ Year - 1995}{25}\right)$$

The constants 0.94 and 0.96 (EIA 2003b, EIA 2003c) represent a 25-year improvement of 6 percent and 4 percent, respectively. The project benefits are in addition to the baseline modifier.

2.2.5.4 Output

The FEDS output for each technology is processed into the following information for direct use by NEMS:

- census division
- building type
- year
- total heating envelope factor adjustment for new buildings
- total cooling envelope factor adjustment for new buildings
- total heating envelope factor adjustment for existing buildings
- total cooling envelope factor adjustment for existing buildings
- lighting load adjustment for new buildings
- lighting load adjustment for existing buildings.

2.3 Spreadsheet Models

Whenever possible, PNNL modeled projects within BEAMS or NEMS-PNNL to help ensure consistency in baseline inputs and methodology. However, we modeled several projects in spreadsheets because of their unique characteristics. The estimated savings generated by the spreadsheet models are entered by fuel type into "fixed" tables within BEAMS so that the environmental and energy cost-savings benefits can be calculated using the same data set as the other projects.

Energy savings estimates developed in spreadsheets require similar types of information as their BEAMS and NEMS-PNNL counterparts. An estimated savings per unit (e.g., energy savings per budget dollar or per household) is applied to an estimated annual forecast of unit sales or installations during the analysis period. Investment costs are also developed. Where possible, baseline data are taken from BEAMS and/or NEMS-PNNL in order to maintain a consistent baseline across projects.

3.0 Technology Diffusion Models – Application to Selected Energy-Efficient Products for Buildings

Diffusion models represent the principal forecasting method for determining potential market penetration for products that have not yet been introduced into the marketplace. Because this situation generally applies to the long-term forecasting horizon of technology assessment models, a means to credibly represent price and policy effects in diffusion models is a key factor in improving the usefulness of market assessment studies. The basic diffusion models assume that the cumulative market penetration follows a characteristic time path (usually in the form of an S-shaped curve).

The dominant type of diffusion model is most likely the mixed-influence model introduced by Frank Bass (1969). The Bass model incorporates parameters that reflect both external (e.g., mass media communication) and internal influences (e.g., word of mouth). In 1998, PNNL conducted a study for DOE/BT to estimate the Bass specification for ten selected energy-efficient building products available in the marketplace today. The results of this work are instrumental in helping to project the likely market pathways of advanced building technologies under development by DOE/BT. This section summarizes the results of that study.

3.1 Scientific and Technical Approach

PNNL conducted a study examining the historical market penetration for ten energy-efficient products related to the buildings sector. Diffusion models were estimated for each product, based on the specification proposed by Bass (1969). The resulting models were intended to help assess technologies supported by BT. This model development and empirical analysis were designed to generate more credible predictions of the adoption process of important energy-efficiency technologies in the buildings sector.

The basic Bass diffusion model, which is possibly the most widely used specification for analyzing market penetration, assumes that the potential market in which the new technology is penetrating is fixed. In reality, the potential market usually is growing in response to a falling price as the manufacturing process and industry structure behind the new technology evolve. This study developed a simple structural model that incorporates these effects and that can be easily estimated from historical data. Given a suitable conceptual model, its parameters can be estimated from data related to several energy technologies.

Most studies of technology adoption have focused either on defining the market potential of the new technology or on the pace at which the technology is adopted. Models that have integrated both aspects generally have not been subjected to historical validation of their underlying parameters. Therefore, in general, little empirical basis exists to suggest which process — diffusion or expanding market potential due to falling costs—might be more influential in driving the penetration of new technologies.

3.2 Background

A report by the Research Triangle Institute for the Electric Power Research Institute (EPRI) (1991) provides a good overview of market penetration approaches. Although the report has a slant toward utilities, much of the discussion applies to all types of energy-saving technologies. The EPRI report clearly distinguishes between two aspects of the process for forecasting market penetration: forecasting market potential and forecasting the rate of market penetration. Forecasting market potential can involve several different concepts of potential, including maximum, technical, and economic potential.

The EPRI report states that the factors affecting the rate of market penetration are predominantly different from factors affecting market potential. For example, comparative advantage—often determined by economic cost—strongly affects market potential. However, comparative advantage doesn't appear to have as strong an effect on the rate of market penetration.

In trying to distinguish the key factors affecting potential vs. penetration, EPRI suggests that market potential is predominantly influenced by the following:

- the market population and demographic trends
- the needs of the market: customer perceptions, attitudes, and beliefs
- feasibility of the product, which depends on functional characteristics of the product and its economic advantages compared with alternatives.

According to EPRI, the rate of market penetration is predominantly influenced by other factors:

- Marketing effort, such as promotion, advertising, and product positioning
- Product characteristics, such as complexity, compatibility, trialability, and observability
- Characteristics of potential adopters, such as decision-making style, innovativeness, and adoption processes
- Market characteristics, such as macroeconomic conditions, degree of social interaction among potential adopters, and competitive conditions.

Approaches to predicting the diffusion of a new technology generally fall under the category of judgmental methods or model-based methods. Judgmental methods share the common trait that they don't require mathematical models or computations; they rely implicitly on the experience and perceptions of the forecaster. On the other hand, model-based methods use well-specified algorithms to process and analyze data. Therefore, the model-based methods can provide systematic forecasts of market penetration that are reproducible and amenable to being incorporated into broader integrated models.

Model-based methods can be divided into two major categories: extrapolation models and causal models. Extrapolation methods include the following: 1) naive diffusion process models, 2) moving average, 3) exponential smoothing, 4) Census Bureau X-11, 5) Box-Jenkins, and 6) Multivariate Time Series.

Of the extrapolation methods, the diffusion models represent the principal method for dealing with products that have not yet been introduced. Because this situation generally applies to long-range models, the discussion will be restricted to these models.

Diffusion models assume that the cumulative market penetration follows a characteristic time path (usually in the form of an S-shaped curve). An apt analogy is the spread of contagious disease in a fixed population. Once begun, growth of the disease in the number of infected individuals may follow a stable, predictable path. The time path of the infection in the population depends on the probability of spontaneous infection, the share of infected individuals, and probability of uninfected individuals interacting with individuals already infected. The notion underlying penetration rate models is that information about the new technology—sufficient to induce its adoption—is similar to an infectious disease (although with a much more positive connotation). This model provides the rationale behind the S-shaped ("logistic") penetration curves that are often observed.

3.3 Bass Diffusion Model

Perhaps the dominant type of diffusion model is the mixed-influence model introduced by Bass in the late 1960s. This two-parameter model incorporates parameters that reflect both external and internal influences. The external influence (corresponding to the "spontaneous" infection mentioned above) is exemplified by mass media communication, size of sales force, or other structured channels of information. Spontaneous refers to the adopter not being influenced by previous adopters but by advertising or some other external change-agent.

In contrast, the internal influence is intended to capture interpersonal communication or word of mouth (i.e., the contagious aspect of the disease analogy above). This also has been termed the imitative effect; the decision to adopt is made only after being influenced by prior adopters. The basic specification of the Bass model is as follows (Bass 1969):

$$\frac{dN(t)}{dt} = [p + \frac{q}{M} \times N(t)] \times [M - N(t)] \tag{3-1}$$

Where
N(t) = cumulative number of adoptions at time *t*
M = market potential, a constant
p = the coefficient of innovation or external influence
q = the coefficient of imitation or internal influence.

Equation 3-1 states that the rate of change in the cumulative number of adopters (dN(t)/dt) is proportional to the difference between the market potential M and the number of previous adopters. The proportionality factor [p + q/M×N(t)] can be interpreted as the probability of adoption at time *t*. This probability is composed of two components: p is interpreted as the probability of spontaneous adoption. The term [q/M×N(t)] relates to the probability that adoption will be chosen based on the influence of previous adopters. This probability grows as the number of adopters increases.

To simplify the presentation, Equation 3-1 can be reoriented in terms of the fraction of the market *(F)* that is being penetrated rather than the absolute number of adopters. In this case, the market potential can be defined as 1.0. This simplified expression in Equation 3-2 now relates to the change in relative cumulative adoptions:

$$\frac{dF(t)}{dt} = [p + qF(t)] \times [1 - F(t)] \tag{3-2}$$

The number of cumulative adoptions at any time, *F(t)*, can be solved by specifying an initial condition that the number of adopters at $t = 0$ is 0. This solution is as follows (Bass 1969):

$$F(t) = \frac{1 - \exp(-(p+q)t)}{1 + (q/p)\exp(-(p+q)t)} \tag{3-3}$$

The basic diffusion models therefore separate the issue of market penetration rate from market potential. That is why the model in Equation 3-3 can be compared across technologies—the percentage change in the total penetration does not depend on the size of the market but only on the parameters *p* and *q*. This overcomes the limiting assumption mentioned above that the market segments, in unit terms, are fixed through time.

3.4 Estimation Issues

Issues related to the appropriate estimation procedures for the Bass diffusion model spawned a considerable literature. At least four estimation procedures were proposed by various researchers: 1) ordinary least squares (Bass 1969), 2) maximum likelihood estimators (Schmittlein and Mahajan 1982), 3) nonlinear least squares (Srinivasan and Mason 1986); Jain and Rao 1989), and 4) algebraic estimation (Mahajan and Sharma 1986).

Mahajan et al. (1986) performed a comparative study of estimation procedures using penetration data for seven products. They concluded that the maximum likelihood and nonlinear least squares procedures provided the best predictions of the four procedures considered. Between those two procedures, nonlinear least squares provided slightly better predictive performance and more valid estimates of the standard errors for the parameter estimates.

As preliminary analysis, PNNL looked at three variants of the nonlinear least squares model. For the first two variants, the focus is on the number of adopters *(X)* in each period. Taking the differences of Equation 3-3 above and including a separate parameter reflects the total number of adopters (m) results in the following for the first variant:

$$X(i) = \frac{m\left(1 - \exp(-(p+q)t_i)\right)}{1 + (q/p) \times \exp(-(p+q)t_i))} - \frac{m\left(1 - \exp(-(p+q)t_{i-1})\right)}{1 + (q/p) \times \exp(-(p+q)t_{i-1}))} + u_i \tag{3-4}$$

where u_i is the error term. Jain and Rao (1989) suggest that the formulation in Equation 3-4 gives the *ex ante* value for X(i) and does not use the *ex post* information on X(1), X(2), …, X(I-1). In the Bass model, the probability that an individual who has not purchased the product up to period t_{i-1} is given by $[F(t_i) - F(t_{i-1})]/((1 - F(t_{i-1})]$. Thus, the number of adopters in the *i*th time interval is as follows:

$$X_i = (m - N(t_{i-1}))\left(\frac{F(t_i) - F(t_{i-1})}{1 - F(t_{i-1})}\right) + v_i \quad (3\text{-}5)$$

where $N(t_{i-1})$ is the cumulative number of adopters up to time t_{i-1}, v_i is the error term, and cumulative distribution function is given by Equation 3-3. This *ex post* estimation procedure proposed by Jain and Rao uses the actual number of cumulative adoptions in the estimation, compared with the *predicted* number in Equation 3-4. Therefore, it is termed the *ex post* estimation in contrast to the *ex ante* estimation.

Mahajan et al. (1986) also point out the possibility of estimating the diffusion curve in level rather than differences form (e.g., cumulative sales rather than annual sales). Thus, the cumulative number of adopters is the dependent variable and the specification becomes the following:

$$N(t_i) = mF(t) = \frac{m\left(1 - \exp(-(p+q)t)\right)}{1 + q/p \times \exp(-(p+q)t)} + w_i \quad (3\text{-}6)$$

where w_i is the error term. As Mahajan et al. (1986) indicate, the errors in Equation 3-6 are likely to be heteroscedastic (i.e., error variance increasing with i) and autocorrelated. Nevertheless, this formulation is somewhat more stable than the differences form and sometimes yields more plausible estimates.

3.5 Results

The results of estimating the Bass (1969) diffusion model for ten energy-related technologies are described below. The technologies were placed into four separate categories: 1) lighting, 2) HVAC and refrigeration (HVAC/R), 3) envelope, and 4) other. Table 3.1 summarizes the technologies for which Bass diffusion models were estimated.

In most of the cases, the technology was not assumed to ultimately capture all of the market, as defined in the fourth column of the table. The maximum market potential was determined judgmentally, on the basis of inspection of the data or from other sources.

Table 3.2 presents the results of the estimation work. The parameter sets labeled in bold are those judged as the most preferred, based on the reasonableness of the estimates and statistical significance. While estimates were developed based on both annual adoptions and cumulative adoptions, at this point, estimates based on annual adoptions have been used. The annual adoption rates are expressed as a fraction of the total potential market and the maximum fraction of the total market potential is expressed exogenously. The first and third groups of estimates reflect an effort to allow the data to suggest the maximum market potential (m rather than m^*).

Table 3.1. Summaries of Technologies Analyzed

Technology	Start Year	End Year	Market Definition
Lighting			
Electronic Ballast	1986	1997	Corrected Power-Factor Ballasts
Compact Fluorescent	1986	1994	Incandescent, 15-150 Watt
T-8 Lamps	1986	1994	Fluorescent lamps, >30 Watt
HVAC and Refrigeration			
Electric Heat Pump	1970	1995	Residential Furnaces
Flame Retention Burner	1975	1987	All Oil Burners
Condensing Gas Furnace	1982	1997	Gas Furnaces
Advanced Compressor	1982	1995	No. of Supermarkets
Room Air Conditioners	1949	1961	No. of Households
Envelope Technologies			
Low-E Window	1983	1996	Residential Windows
Other			
DOE-2 Bldg Model[f]	1984	1994	Commercial Buildings Designed

Examination of the estimated coefficients indicates that the estimates of the external influence parameter are much more variable than those for the internal influence parameter. One of the lowest values of the internal influence coefficient is found for CFLs; this coefficient reflects the lamps extremely slow initial penetration into the market. In addition to the lamp's high initial price, Haddad (1994) suggests that industrial organization, retail incentives, and social convention are additional reasons for the atypically slow adoption of this technology. On the other extreme is the flame retention oil burner, whose adoption was accelerated by the increase in oil prices during the Iranian revolution in the late 1970s. In spite of these extremes, the simple average internal influence coefficient of 0.38 is the same as the average for 213 technologies as reported by Sultan, Farley, and Lehmann (1990). In that study, the average external influence was 0.03 compared with an average 0.018 for the ten energy-related technologies.

[f] Our diffusion curve work was performed prior to the NRC 2001 report, which raised serious concerns regarding the actual penetration of DOE-2 into the building design marketplace. Although parameters for DOE-2 were developed in the original work, their influence has been removed from the generic diffusion curves developed by PNNL and used in the GPRA process.

Table 3.2. Diffusion Curve Parameter Results

Product	Annual Sales						Cumulative Sales					
	p	q	m	p	q	m*	p	q	m	p	q	m*
Electronic Ballasts	0.0054 (0.6)	0.6489 (2.5)	0.4815 (3.4)	**0.0138** (1.1)	**0.3729** (3.3)	**0.6**	0.0037 (2.1)	0.7006 (7.3)	0.4627 (19.5)	0.0092 (3.3)	439 (9.3)	0.6
Compact Fluorescent				**0.0075**	**0.071**	**0.50**						
T-8 Lamps				**0.0041**	**0.326**	**0.80**						
Electric Heat Pump				**0.0118**	**0.459**	**0.23**	0.0054 (1.6)	0.6228 (5.9)	0.2169 (43.9)	0.0112 (2.2)	0.4588 (6.3)	0.23
Flame Retention Burner				**0.0039**	**0.655**	**1.0**	<0.001 (0.3)	1.774 (3.7)	0.8143 (23.9)	0.0040 (1.1)	0.655 (4.6)	1.0
Condensing Gas Furnace				**0.070** (1.8)	**0.071** (0.8)	**0.3**	0.0782 (3.6)	0.2082 (1.8)	0.238 (14.7)	0.0881 (6.1)	0.0240 (0.6)	0.3
Room Air Conditioners				**0.0072**	**0.423**	**0.33**						
Advanced Compressors	.0232 (9.6)	0.2788 (11.3)	0.9514 (21.3)	**0.0247** (11.2)	**0.2483** (22.1)	**1.0**	0.0242 (31.4)	0.2633 (20.5)	0.9801 (39.8)			
Low-E Windows	0.0562 (8.2)	0.2936 (7.3)	0.3663 (18.3)	**0.0577** (9.6)	**0.2729** (14.3)	**0.37**				0.0565 (25.0)	0.2819 (27.3)	0.37
DOE-2 Building Model	0.00001 (0.5)	1.18 (4.8)	0.279 (6.4)	**0.0005**	**0.656**	**0.50**						

p represents the coefficient of innovation (external influence)

q represents the coefficient of imitation (internal influence)

m is the maximum market potential suggested by the data

m* is an assumed value taken from graphical output

The first and third groups of estimates reflect the results when all three parameters (p, q, and m) are estimated based on the data.

The second and fourth groups of estimates reflect the results when two parameters (p and q) are estimated, with m (as m*) set based on graphical output

Values in parentheses are t-values, where available.

3.5.1 Lighting Technologies

As Table 3.1 outlines, the generic lighting diffusion curve is based on the market penetration of the electronic ballast, compact fluorescent, and T-8 lamp technologies. Tables 3.3 through 3.5 and Figures 3.1 through 3.3 detail the penetration of these technologies and chart the predicted penetration rates. To develop a generic lighting curve, the three lighting technology curves were normalized by setting m* (the maximum market potential) to 1.0. By plotting the three curves using the normalized market potential, a generic curve was specified by visual determination. The resulting parameters for the generic lighting curve are 0.005 (external, or p) and 0.25 (internal, or q). Figure 3.4 charts the diffusion curves for the three technologies and the generic lighting curve.

Table 3.3. Ballast Shipments and Penetration of Electronic Ballasts

Year	Corrected Power-Factor Type (magnetic) (million)	Electronic Type (million)	Total Ballast Shipments (million)	Penetration of Electronic type (fraction)
1986	52.04	0.43	52.47	0.008
1987	54.75	0.65	55.40	0.012
1988	56.80	1.06	57.86	0.018
1989	58.27	1.43	59.70	0.024
1990	55.81	3.00	58.81	0.051
1991	55.47	8.34	63.81	0.131
1992	55.38	13.29	68.67	0.194
1993	54.79	24.49	79.28	0.309
1994	55.99	24.61	80.60	0.305
1995	47.65	32.90	80.55	0.408
1996	42.84	30.34	73.18	0.415
1997	42.89	36.54	79.43	0.460
1998	42.58	39.84	82.42	0.483
1999	41.44	41.63	83.07	0.501
2000	37.54	49.32	86.86	0.568
Source: Bureau of the Census, Current Industrial Reports (ESA 1997, 2002).				

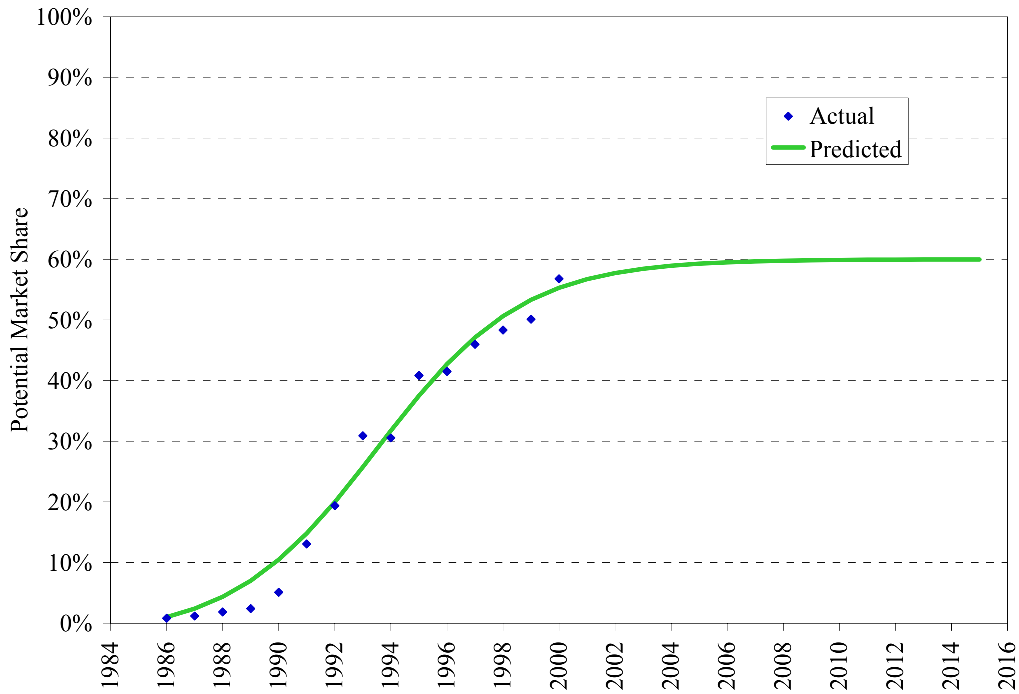

Figure 3.1. Actual and Predicted Penetration Rates: Electronic Ballasts

Table 3.4. Total Fluorescent Tube and T-8 Tube Shipments

Year	Conventional Fluorescent (1)			Linear T-8 (million)	Data Source for T-8
	Low-Power (million)(2)	High-Power (million)	Total (million)(3)		
1985	45	255	300	0	estimate
1986	45	270	315	0.5	estimate
1987	45.7	287	332.7	1	estimate
1988	50	300	350	2	EPRI (4)
1989	55	315	370	3.1	EPRI
1990	62	332.8	394.8	5.7	EPRI
1991	69.3	353.1	422.4	15	estimate
1992	70.3	367.4	437.7	27.7	CIR (5)
1993	71.5	389.9	461.4	43.8	CIR
1994	78.4	399.7	478.1	56.1	CIR

(1) "Conventional Fluorescent" corresponds to the Census Bureau's category of "Other Fluorescent Lamps"; excludes slimline, circular, and high-output 800 milliamp or more. Includes T-8 Lamps.

(2) Low-power is defined as 40 watts or less prior to 1992, 30 watts from 1992 through 1994. No adjustment was made to achieve definitional consistency.

(3) Values for conventional fluorescent are estimated for 1985, 1986, 1988 and 1989.

(4) EPRI 1992.

(5) CIR: Current Industrial Reports, MQ36B series.

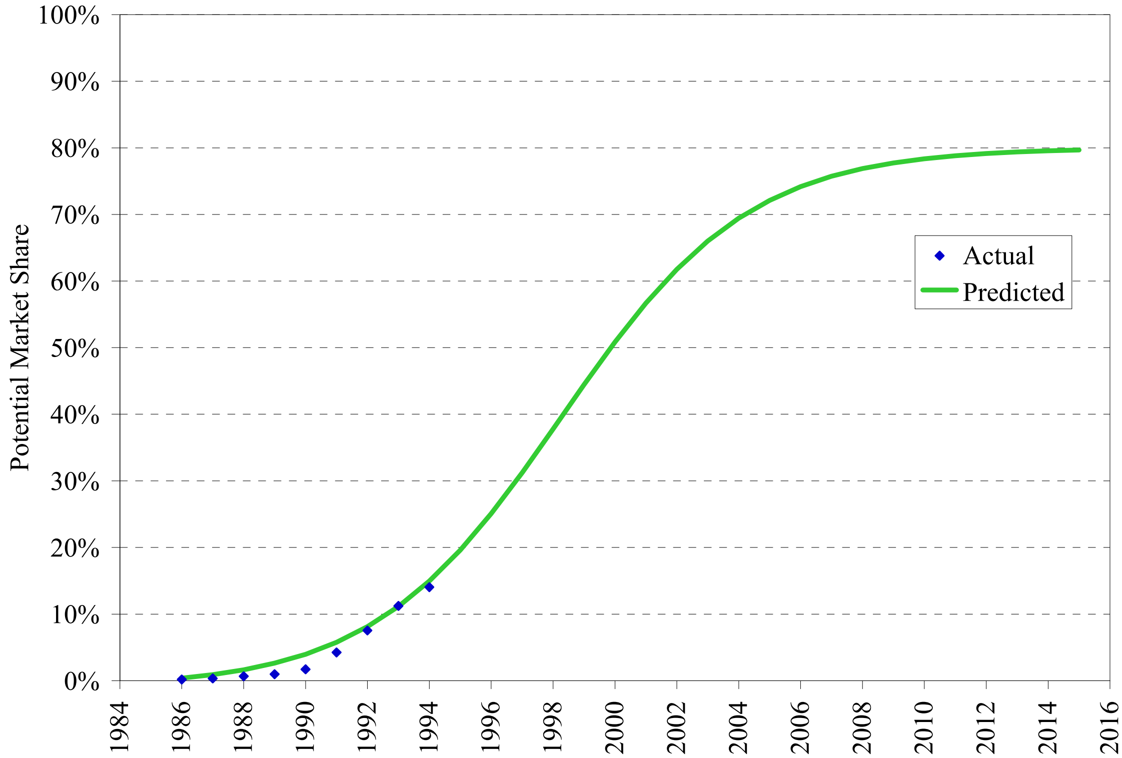

Figure 3.2. Actual and Predicted Penetration Rates: T-8 Lamps

Table 3.5. Shipments and Penetration of CFLs

Year	Incandes. 15-150 watt (million)	CFLs (million)	Total (million)	Market Penetration	Data Sources	
					Incandes.	CFL
1986	800.0	2.0	802.0	0.0025	estimate	estimate
1987	800.0	4.0	804.0	0.0050	estimate	estimate
1988	800.0	9.9	809.9	0.0122	estimate	EPRI
1989	810.7	11.6	822.3	0.0141	CIR*	EPRI
1990	798.6	16.7	815.3	0.0205	CIR	EPRI
1991	783.0	25.2	808.2	0.0312	CIR	estimate
1992	795.5	30.4	825.9	0.0368	CIR	CIR
1993	847.1	33.4	880.5	0.0379	CIR	CIR
1994	818.8	35.8	854.6	0.0419	CIR	CIR

Source: EPRI 1992.

*CIR: Current Industrial Reports, Bureau of the Census, MQ36B, various issues.

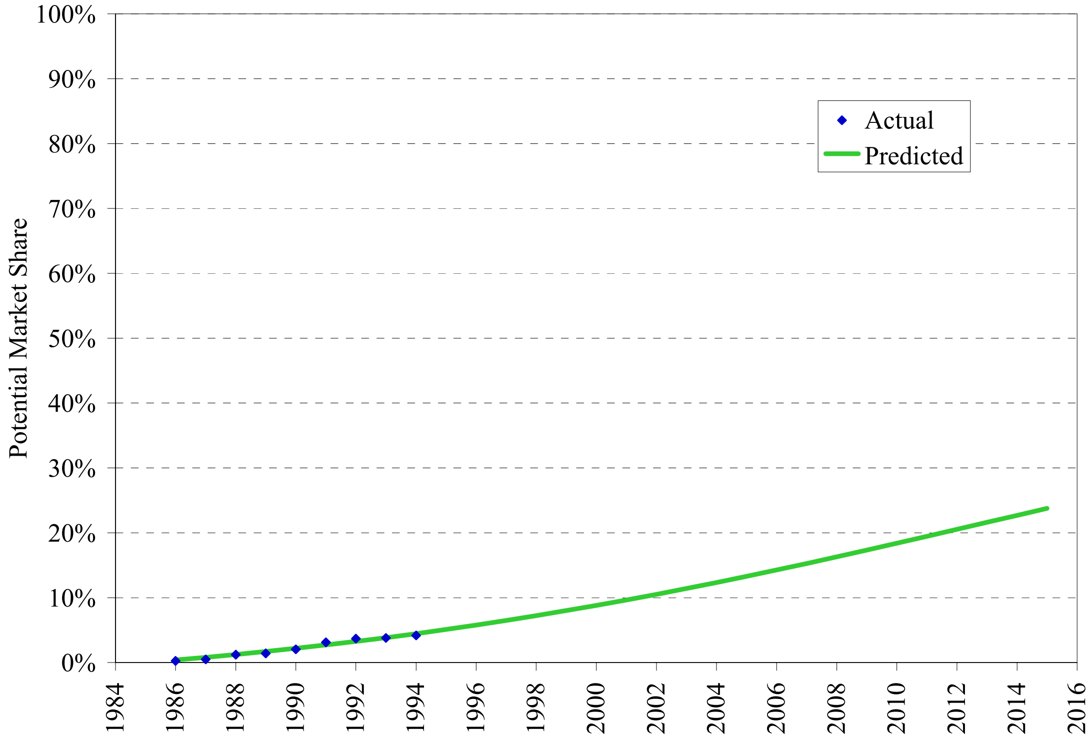

Figure 3.3. Actual and Predicted Penetration Rates: CFLs

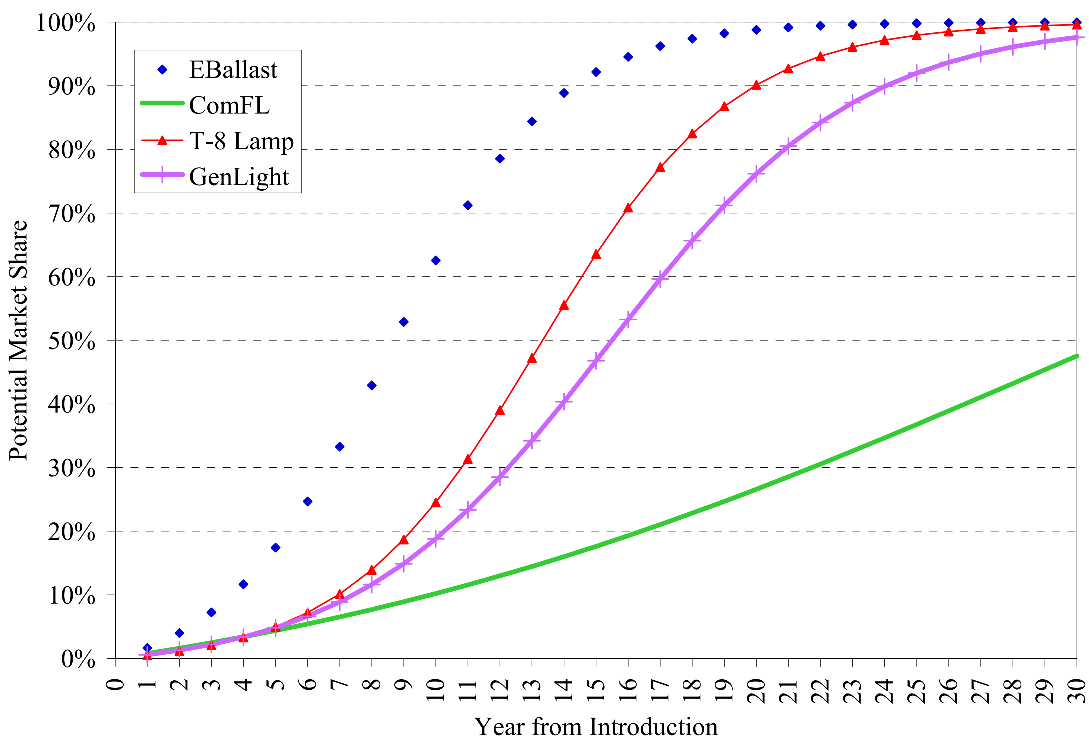

Figure 3.4. Generic Lighting Diffusion Curve Compared With Other Lighting Technology Curves (Normalized to m* = 1.0)

3.5.2 HVAC Technologies

As Table 3.1 outlines, the generic HVAC diffusion curve is based on the market penetration of the electric heat pump, flame retention burner, condensing gas furnace, and room air conditioners technologies. Tables 3.6 through 3.9 and Figures 3.5 through 3.8 detail the penetration of these technologies and the predicted penetration rates. To develop a generic HVAC curve, the four HVAC technology curves were normalized by setting m* (the maximum market potential) to 1.0. By plotting the four curves using the normalized market potential, a generic curve was specified by visual determination. The resulting parameters for the generic HVAC curve are 0.02 (external, or p) and 0.3 (internal, or q). Figure 3.9 charts the diffusion curves for the four technologies and the generic HVAC curve.

Table 3.6. Advanced Electric Heat Pump Shipments and Penetration

Year	Gas Furnaces (thousands)	Electric Furnaces (thousands)	Split System Heat Pumps (thousands)	Total (thousands)	HP Market Penetration (fraction)
1970	1471.2	105.3	33.6	1610.1	0.021
1971	1795.2	193.8	26.6	2015.6	0.013
1972	2066.2	288.5	32.3	2387.0	0.014
1973	1719.5	370.2	43.9	2133.6	0.021
1974	1476.3	406.8	56.6	1939.7	0.029
1975	1185.8	252.3	92.8	1530.9	0.061
1976	1544.4	338.9	202.0	2085.3	0.097
1977	1508.1	283.6	356.8	2148.5	0.166
1978	1636.1	360.0	420.8	2416.9	0.174
1979	1862.6	360.0	407.6	2630.2	0.155
1980	1445.7	360.0	323.4	2129.1	0.152
1981	1416.7	360.0	390.4	2167.1	0.180
1982	1155.6	300.0	300.9	1756.5	0.171
1983	1661.8	360.0	509.6	2531.4	0.201
1984	1849.2	360.0	603.1	2812.3	0.214
1985	1822.3	370.0	665.2	2857.5	0.233
1986	2104.8	382.6	728.3	3215.7	0.226
1987	2072.9	375.1	754.6	3202.6	0.236
1988	2092.2	293.1	680.9	3066.2	0.222
1989	2162.2	298.2	690.0	3150.4	0.219
1990	1950.5	280.0	667.4	2897.9	0.230
1991	2056.7	245.2	637.1	2939.0	0.217
1992	2106.9	290.2	670.0	3067.1	0.218
1993	2584.6	348.5	747.5	3680.6	0.203
1994	2696.8	400.8	857.6	3955.2	0.217
1995	2601.0	402.0	866.6	3869.6	0.224

Sources: For gas furnaces the source is the Census of Manufactures, 1972 and 1977 (DOC 1973, 1978); PNNL estimates are for the intervening years; and the Gas Appliance Manufacturers Association (GAMA) estimates are for years 1986-1995.

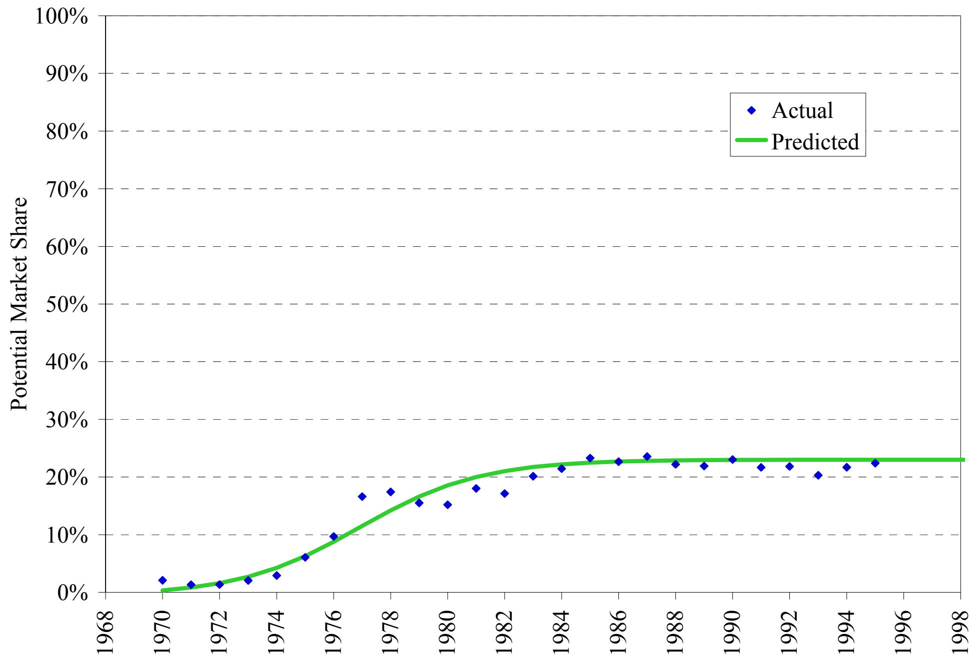

Figure 3.5. Actual and Predicted Market Penetration: Electric Heat Pumps

Table 3.7. Sales and Market Penetration of Flame Retention Head Oil Burners (FRHOBs)

	Annual Oil Burner Sales(1) (thousand)	**Cumulative FRHOB Sales(2) (thousand)**	**Annual FRHOB Sales(3) (thousand)**	**FRHOB Market Share(4) (fraction)**
1975	750	20	20	0.027
1976	750	50	30	0.040
1977	749	70	20	0.027
1978	777	100	30	0.039
1979	735	125	25	0.034
1980	585	250	125	0.214
1981	606	400	150	0.248
1982	522	800	400	0.766
1983	512	1200	400	0.781
1984	510	1600	400	0.784
1985	536	2000	400	0.746
1986	555	2450	450	0.811
1987	577	2950	500	0.867

(1) Annual oil burner sales data from 1977-1987 were obtained through a telephone interview with Don Farrell, using data files maintained by *Fuel Oil and Oil Heat Magazine*. Data for 1975 and 1976 are PNNL estimates.

(2) Cumulative sales for FRHOBs were obtained from ORNL report by Brown et al. (1989), Figure 4.3, p. 55.

(3) Annual FRHOB sales data were estimated as the difference in cumulative sales in Column

(4) Market share of FRHOB is the ratio of FRHOB sales over total burner sales.

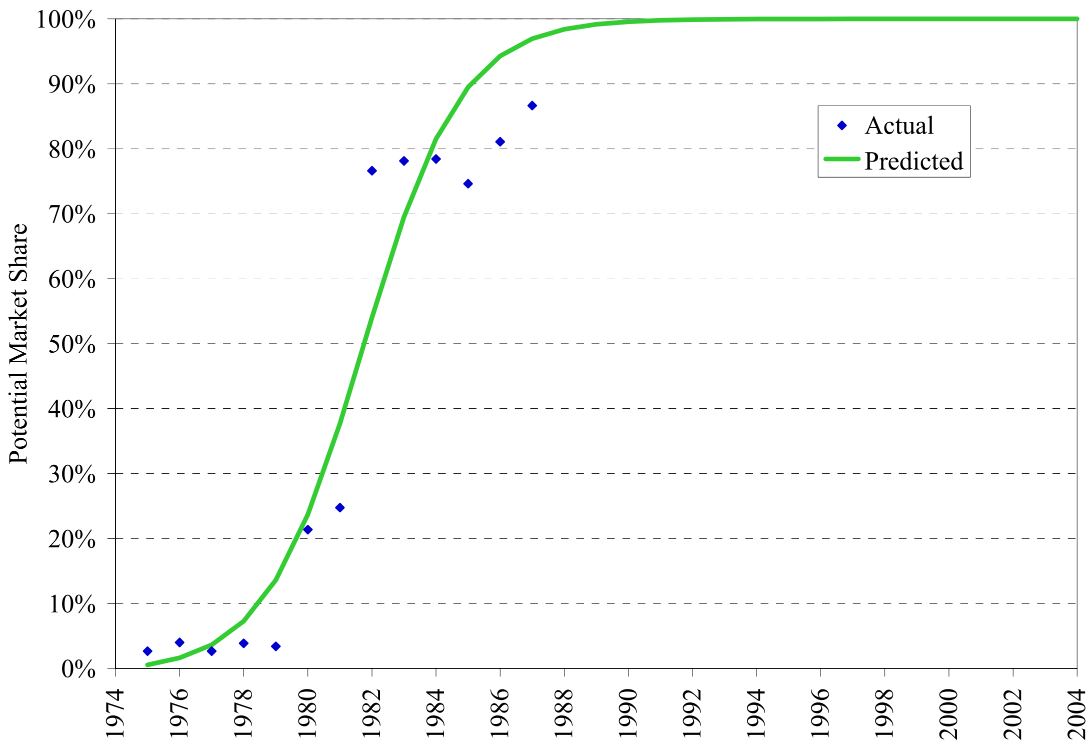

Figure 3.6. Actual and Predicted Market Penetration Rates: Flame Retention Oil Burners

Table 3.8. Market Penetration of High Efficiency Gas Furnaces

Year	Market Share	Source
1981	0.005	PNNL Estimate
1982	0.010	PNNL Estimate
1983	0.040	PNNL Estimate
1984	0.111	GAMA
1985	0.123	GAMA
1986	0.158	GAMA
1987	0.160	PNNL Estimate
1988	0.165	PNNL Estimate
1989	0.170	PNNL Estimate
1990	0.175	GAMA
1991	0.205	GAMA
1992	0.210	PNNL Estimate
1993	0.210	PNNL Estimate
1994	0.214	GAMA
1995	0.223	GAMA
1996	0.235	GAMA
1997	0.253	GAMA
1998	0.240	PNNL Estimate
1999	0.233	GAMA
2000	0.236	GAMA
2001	0.279	GAMA
Note: For 1984-1987, the fraction relates to annual fuel utilization efficiency (AFUE) of 86% and greater. For subsequent periods, the fraction relates to furnaces with AFUE of 88% and greater. Because of some changes in the AFUE testing procedures, these fractions are roughly comparable.		

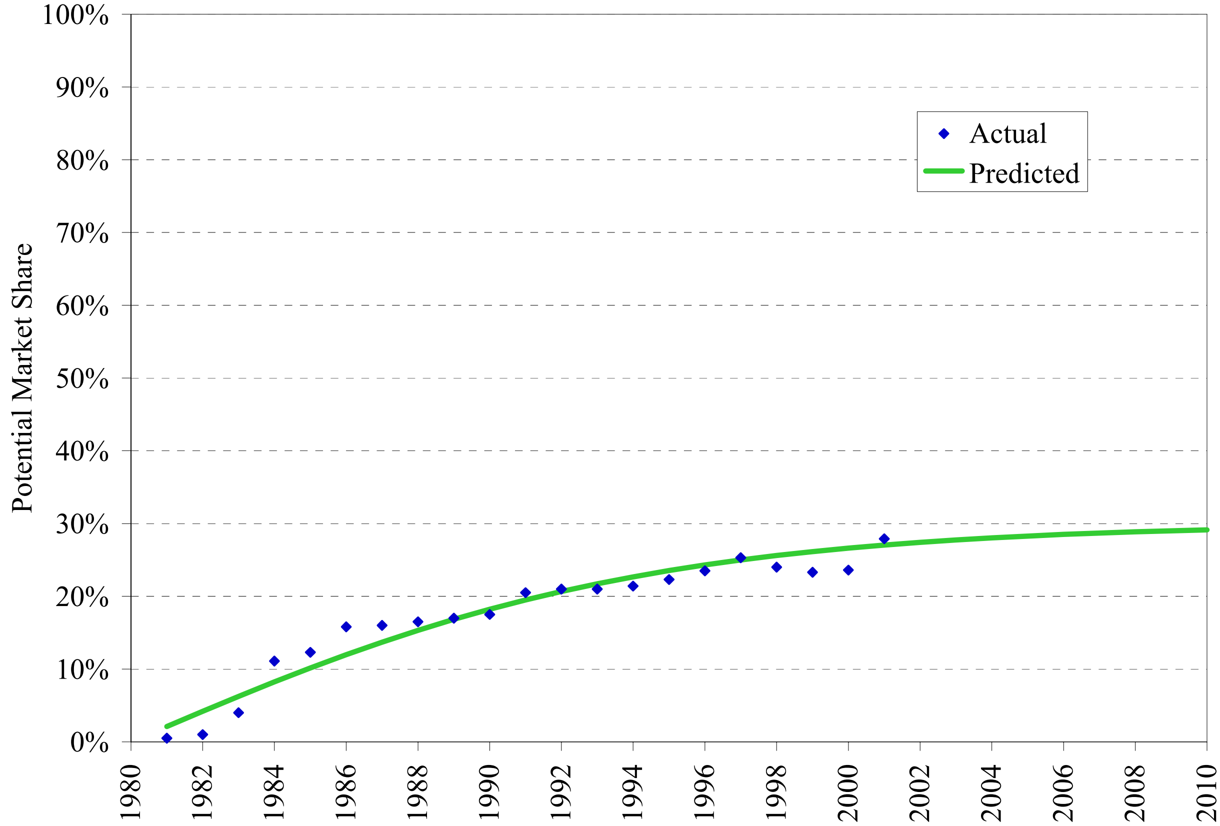

Figure 3.7. Actual and Predicted Market Penetration for Condensing Gas Furnaces

Table 3.9. Room Air Conditioner Sales

Year	Sales (thousands)
1949	96
1950	195
1951	238
1952	380
1953	1045
1954	1230
1955	1267
1956	1828
1957	1586
1958	1673
1959	1800
1960	1580
1961	1500
Source: Mahajan et al. (1986).	

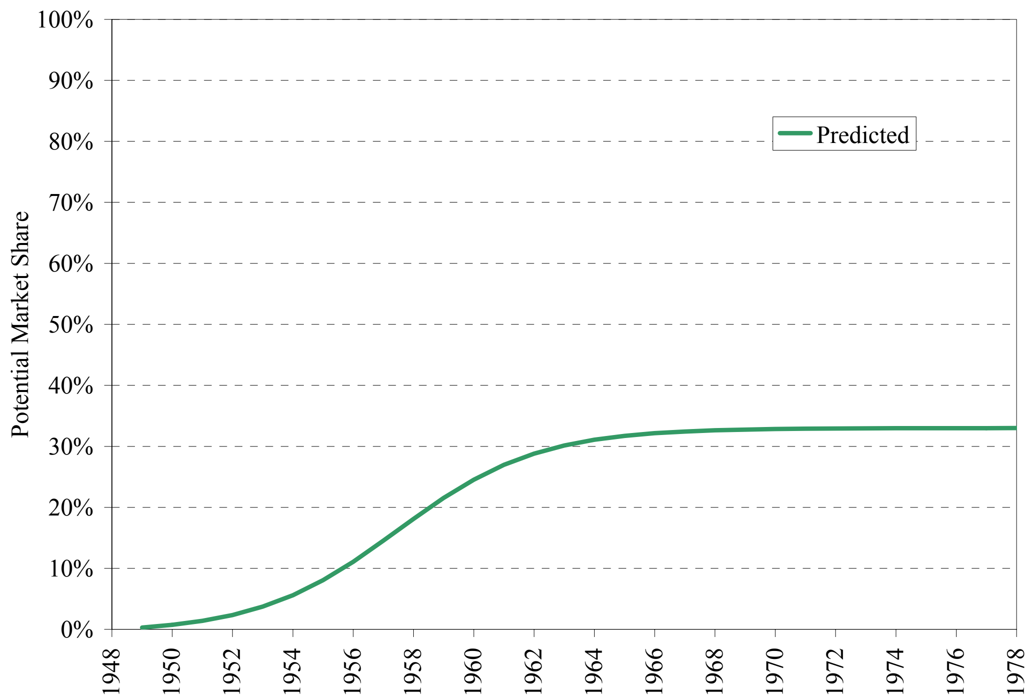

Figure 3.8. Predicted Market Penetration of Room Air Conditioners

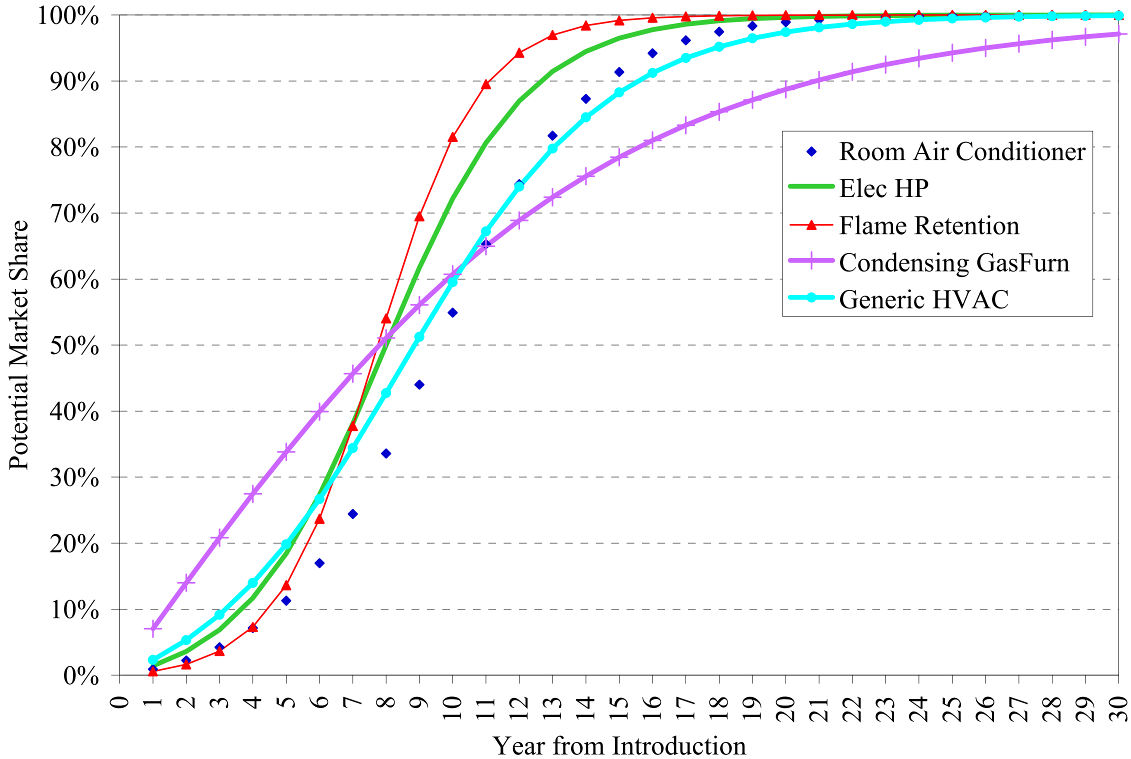

Figure 3.9. Generic HVAC Diffusion Curve Compared With Other HVAC Technology Curves (Normalized to m* = 1.0)

3.5.3 Envelope and Other Technologies

Two other technologies were also studied and form the basis for the generic envelope and other technologies diffusion curve. The generic envelope/other diffusion curve is based on the market penetration of the advanced compressor and low-E window technologies.[g] Tables 3-10 and 3-11 and Figures 3-10 and 3-11 detail the penetration of these technologies and chart the predicted penetration rates. To develop a generic envelope/other curve, the two technology curves were normalized by setting m* (the maximum market potential) to 1.0. By plotting the two curves using the normalized market potential, a generic curve was specified by visual determination. The resulting parameters for the generic envelope/other curve are 0.04 (external, or p) and 0.26 (internal, or q). Figure 3.12 charts the diffusion curves for the two technologies and the generic Envelope/Other curve.

[g] The influence of the DOE-2 estimates has been removed in the estimation process for the generic curve.

Table 3.10. Market Penetration of High-Efficiency Refrigerator Compressors for Supermarkets

Year	Market Penetration (fraction)
1982	0.03
1983	0.06
1984	0.11
1985	0.16
1986	0.21
1987	0.27
1988	0.34
1989	0.41
1990	0.50
1991	0.58
1992	0.65
1993	0.71
1994	0.76
1995	0.80
Source: Geller and McGaraghan 1996, Figure 3.	

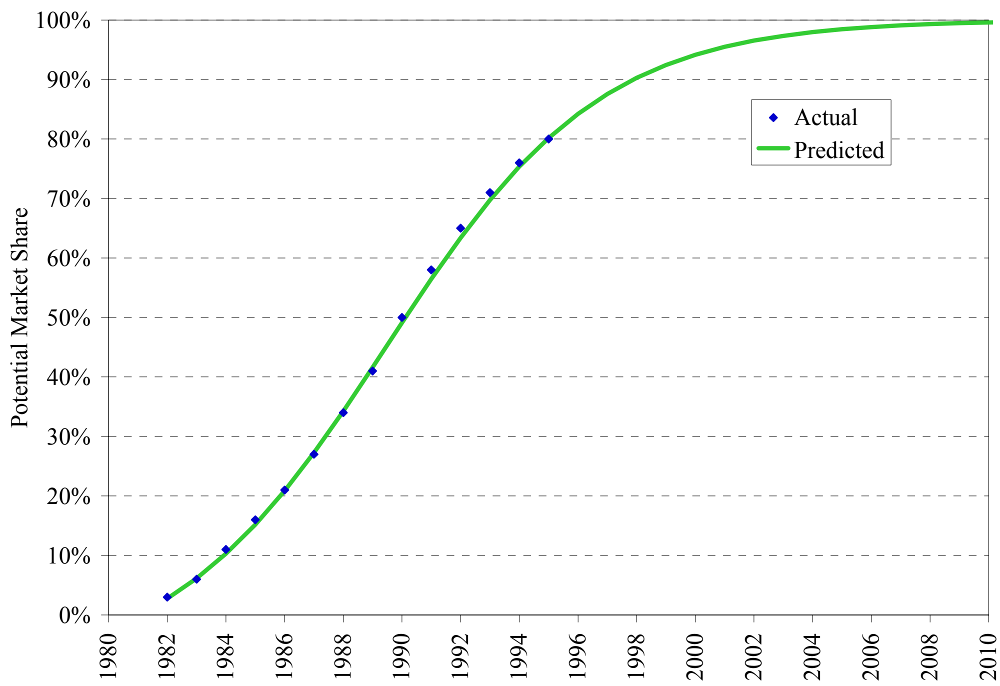

Figure 3.10. Actual and Predicted Market Penetration Rates: Advanced Refrigeration Compressors for Supermarkets

Table 3.11. Market Penetration of Low-E Residential Windows

Year	Market Penetration (fraction)	Source
1983	0.01	PNNL Estimate(1)
1984	0.02	PNNL Estimate(1)
1985	0.05	PNNL Estimate(1)
1986	0.12	ACEEE(2)
1987	0.16	PNNL Estimate(3)
1988	0.20	PNNL Estimate(3)
1989	0.23	PNNL Estimate(3)
1990	0.26	PNNL Estimate(3)
1991	0.28	AAMA(4)
1992	0.30	PNNL Estimate
1993	0.32	AAMA(4)
1994	0.34	PNNL Estimate
1995	0.35	AAMA(4)
1996	0.35	LBNL(5)

(1) Accelerating penetration consistent with 12% share in Geller and McGaraghan 1996.
(2) Geller and McGaraghan 1996, Figure 1.
(3) Interpolated in a manner to show declining rates of increase.
(4) Study of U.S. Market for Windows and Doors, American Architectural Manufacturers Association (AAMA), 1996.
(5) Personal communication with D. Arasteh, LBNL, on June 11, 1998.

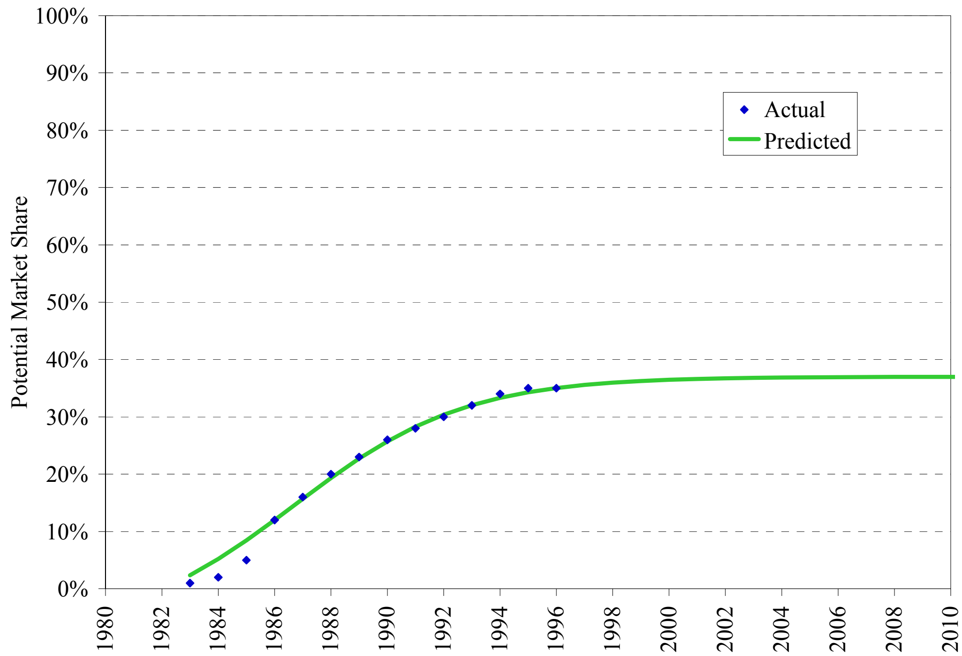

Figure 3.11. Actual and Predicted Market Penetration Rates: Residential Low-E Windows

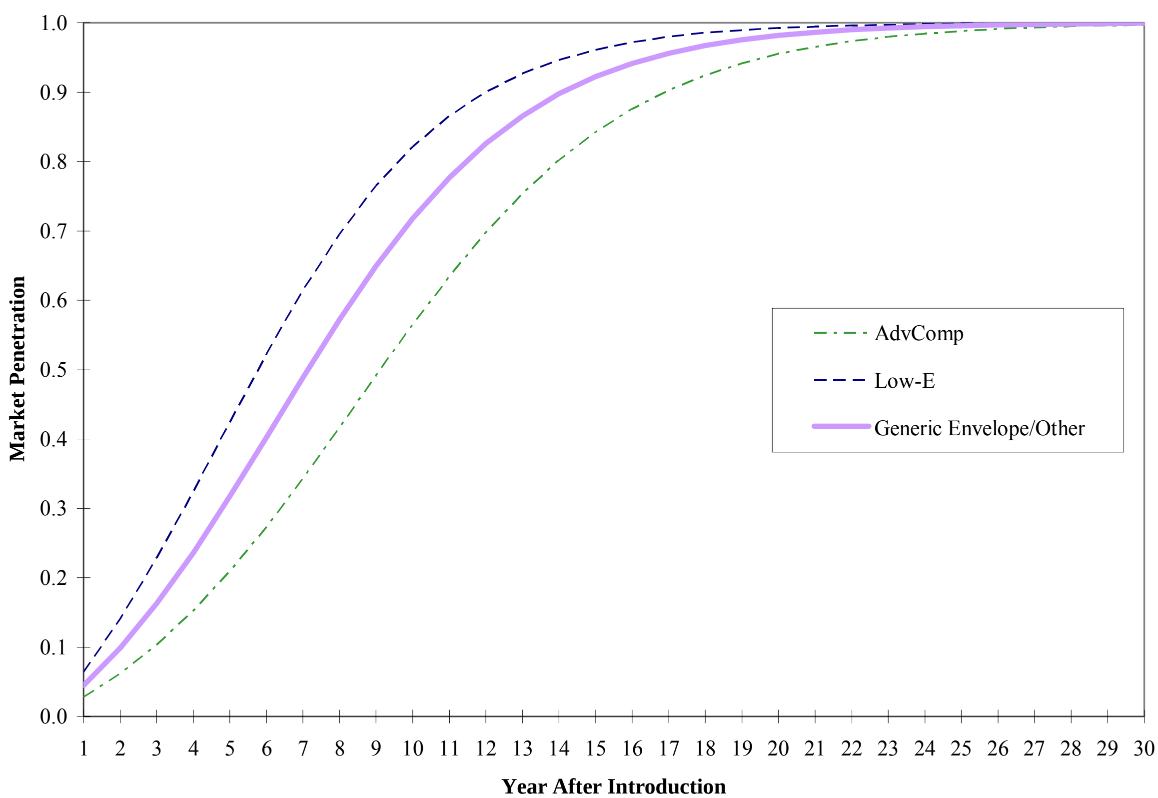

Figure 3.12. Generic Envelope/Other Diffusion Curve Compared With Other Technology Curves (Normalized to m* = 1.0)

3.6 Use of the Generic Curves within the GPRA Analysis

PNNL used the generic diffusion curves to generate market penetration estimates for buildings-related projects that do not have a forecast of annual sales targets. We created a simple penetration model spreadsheet to generate buildings-related project-specific diffusion curves for input to the BEAMS model. Within the spreadsheet, the user specifies the year of market introduction for the project, the expected maximum market potential in 2020, and the technology classification that best resembles the project (lighting, HVAC, envelope, or other project).

Some of the estimated buildings-related project diffusion curves stray from the generic classifications, depending on their individual characteristics, and use one of the specific technology parameter sets in Table 3.2.

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