Assessing the Impacts of Energy Saving Products and Technologies: The Importance of Revealing Underlying Assumptions

Martha Brook, California Energy Commission
David M. Anderson, Michael R. Brambley, and Michael Kintner-Meyer, Pacific Northwest National Laboratory[1]

ABSTRACT

In a world of limited financial resources, funders of energy-efficiency research are faced daily with the need to select a few investment opportunities to pursue from the spectrum of all possible project investments. Usually the goal is to identify projects with the highest likely energy savings and environmental benefits per dollar invested. Predicting impacts, however, is difficult because of numerous uncertainties in future economic conditions and the evolution from a research project to a final commercial product. Future prices of energy are unknown, the costs of products likely to emerge from research and development (R&D) are highly uncertain, and the rates of penetration of the resulting products into the market are unknown and dependent on many factors related to marketing, product packaging, and delivery channels to the ultimate end-user.

Recognizing this challenge, the California Energy Commission's Public Interest Energy Research (PIER) Program on Buildings funded development of a method for projecting the energy and peak load reduction impacts of products likely to result from building-efficiency R&D projects. This method was to be based on sound methodological principles and to explicitly reveal all important underlying assumptions so estimates could be compared and assumptions understood and adjusted to the same basis if necessary for comparison.

This paper describes the methodology developed, presents results of applying it to a sample of products emerging from PIER-funded research, and identifies some key drivers of the impact analysis. It also discusses how assessment methods based on technical potential alone without considering the trajectory of market penetration over time can provide misleadingly optimistic estimates of impacts. The paper concludes with key observations on how the assessment methodology might be used most effectively in making R&D investment decisions and where it might be misused or where results might be misleading.

Introduction

As stewards of public interest funds, the California Energy Commission's Public Interest Energy Research (PIER) Program must justify the investment of research monies into specific areas by the magnitude of the future benefits to California's electricity ratepayers. PIER's Buildings Program funded development of an impact assessment methodology for building-related energy efficient technologies and practices. The intent of this project was to develop a framework for estimating future electric energy savings and demand reductions as a result of the market adoption of PIER-funded research products. Opportunities to invest in the development of technologies or practices that have the potential to improve the energy efficiency of buildings

[1] Operated for the U.S. Department of Energy by Battelle Memorial Institute under Contract DE-AC06-76RL01830

are plentiful, and research funds are limited. Assessing the future impacts of proposed research, as well as refining expectations of the benefits from completed R&D projects, are ongoing efforts that the PIER Buildings Program performs to prioritize new research funding and to publish project results.

Desirable Characteristics of an Assessment Methodology

When making building energy research investment decisions, it is important to use a consistent and transparent methodology that accounts for the energy saving and demand reduction potential of a technology, the size of the building market that will be able to implement the technology, and the probability that the technology will be chosen or adopted by this market over time. This methodology must be able to assess the technical potential of technologies and strategies that may influence building energy performance in a number of ways, and at various stages of a building's life cycle. California's building population contains a large diversity of building types, occupant and business characteristics, and energy using equipment and appliances. A methodology to assess research products that will impact specific markets within this building population must be able to characterize a wide range of possible markets. For each technology assessment, the market characterization needs to include estimates of 1) the size, in terms of energy and peak demand, of the market segment that is able to employ the technology, and 2) the portion of the market segment that is likely to adopt the technology over time. The estimation of market penetration should, if at all possible, account for the fact that there may be other existing and/or emerging technologies "competing" to provide energy performance benefits to the same market segment.

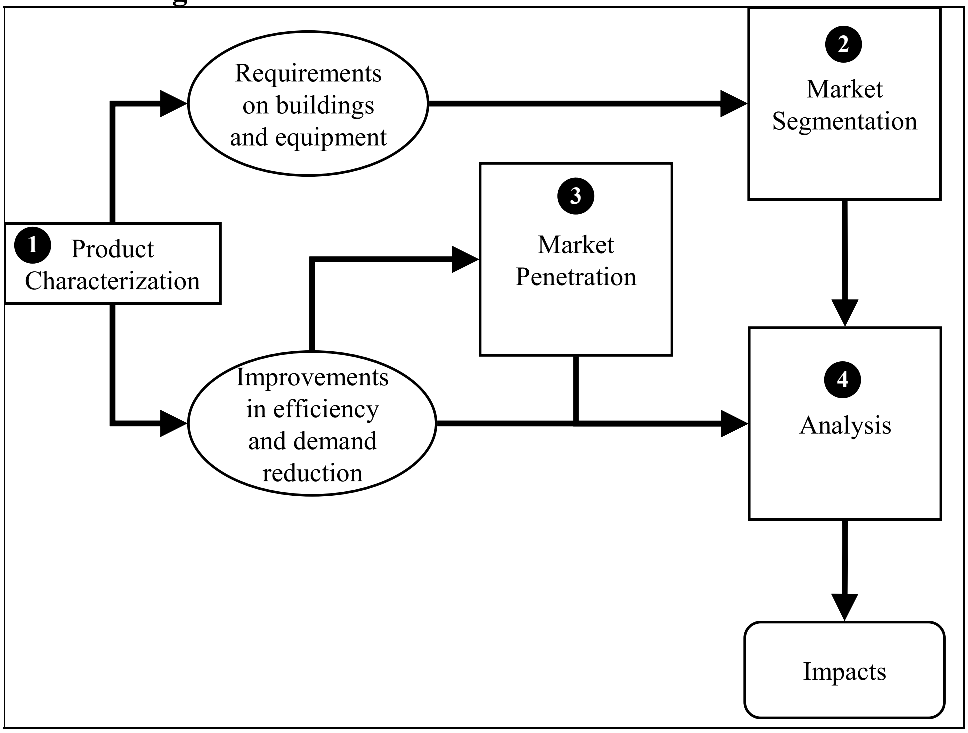
Energy consumption and peak demand data for California buildings is available at many levels of aggregation, but the data varies in quality and appropriateness. At times it may be most effective to estimate the size of a specific market using a combination of several data sources, while at other times the data will reside in a single dataset. A very desirable characteristic of an assessment methodology is the ability to work with varying types and levels of data.

Because multiple estimates are required for each technology assessment, it is important that all underlying assumptions are transparent and easily changeable. There are also uncertainties in each aspect of estimating the energy performance benefits of research products. Ideally, the PIER Buildings Program would be able to vary the estimates of technical potential, market size and market penetration within reasonable bounds, to understand the probable range of future outcomes.

Assessment Methodology

The assessment framework is composed of the following four components that lead to impact estimates: 1) Product Characterization, 2) Market Segmentation, 3) Market Penetration, and 4) Analysis of Impacts. Figure 1 depicts the simplified view of the overall assessment framework.

Figure 1. Overview of the Assessment Framework



This paper discusses each major component and the data requirements necessary to analyze the impacts for a large range of energy efficiency products in buildings, encompassing lighting, heating, ventilation, and air-conditioning (HVAC), envelope, and appliances measures expressed as a new product or as a retrofit opportunity.

Product Characterization

Product characteristics are used for two primary purposes: 1) identification of the buildings on which the products of PIER or other research could be used (market segmentation) and 2) estimation of improvements likely to result from penetration of the products into those buildings (impact analysis). Characteristics used for market segmentation include features of buildings on which the product could be used, local climate, types of equipment and systems present, size of the building, and other factors that determine the suitability of a building for use of the product. Characteristics for estimating impacts include the technical improvements in electricity consumption and peak power use by the product compared to the product it replaces or by the equipment or system on which the product under analysis is installed.

The assignment of reasonable values for the improvement characteristics of new products is an inherent problem in any impact assessment of new products and technologies that have not yet been validated and tested in the field. This assessment framework is no exception. We recommend using the technology developers as the first source from which to gather information about a new product or practice. In some cases, others with expertise in the applicable market or field of application can add additional information and judgment, possibly expanding the perspective provided by the developers.

Market Segmentation

Market segmentation is the process of determining the potential market for a product (i.e., the product's market segment) by using a set of market attributes to identify the maximum scope of opportunity for application of the product. In the context of this project, segmentation is the process of defining that portion of the total commercial buildings market most likely to be affected by a particular research product, and then determining the size of that market segment. Rarely will a product apply to the entire marketplace. Therefore, we segment or attempt to determine the maximum specific portion of the market to which the product is expected to apply.

Once the market segment has been identified, its size must be determined. For use in this assessment methodology, the market segment size must be represented in terms of annual energy consumption (kWh) and peak demand (kW).

Market Penetration

Once the market potential has been identified, the next step is to forecast the rate of market penetration. Market penetration is primarily influenced by the marketing effort (e.g., promotion, advertising), product characteristics (e.g., complexity, compatibility), characteristics of potential adopters (e.g., decision making style, innovativeness), and market characteristics (e.g., macroeconomic conditions, competitive conditions). Two basic approaches to estimating market penetration are provided as part of the framework: 1) method based on expert judgment with the penetration curve constrained to a specific functional form and 2) a model-based method that explicitly accounts for competition between products.

The method based on expert judgment relies on the experience and perceptions of forecasters but is constrained to the "S"-shaped, logit function-based market penetration curve as defined below:

$$M(t) = \frac{\kappa}{1 + e^{-\left(\frac{\ln(81)}{t_s}\right)(t - t_h)}}, \tag{1}$$

where

κ is the total potential market penetration,

t is the time indexed in years,

t_h is the time at which half of the market is penetrated, and

t_s is the time period required to transition from F=0.1 to F=0.9.

Equation (1), a special solution of the Fisher-Pry model, specifies the time period t_s required for the product to go from penetrating 10% to 90% of maximum penetration (Fisher and Pry 1971). The expert assigns values to the parameters (κ, t_h , t_s) that describe the shape of the "S" curve.

The model-based method utilizes a multi-competitor market penetration model developed by Peterka (Peterka 1977). The Peterka model is an extension of the Fisher-Pry model with multiple competitors. The model is based on Peterka's findings in the late 70s that stated that determining factors for market penetration are: 1) specific investment, expressed in dollar per unity of capacity of a product (e.g., kW); 2) specific production cost, expressed in dollars per unit of service (e.g., kWh of cooling/heating energy); and 3) initial market share of competing products. The model requires for each competitor these three inputs, and computes the market shares as a function of time for each product.

It should be noted that both market penetration approaches (expert-judgment-based and the Peterka model) model market competition. The Peterka model explicitly defines market behavior relations of products based on cost and performance of competing products, while the expert-judgment approach represents these mechanisms implicitly expressed through the judgment of experts.

Impact Analysis

Impacts are expressed in terms of cumulative and annual projected reductions in electricity consumption and peak electric demand, and savings on electricity expenditures. The impact estimations were performed based on the following equations (Kintner-Meyer et al. 2003):

Annual Electric Energy Savings

$$SE(t) = \sum_{j=1}^{m} \left(E_j(t) \cdot IE_j \cdot M_j(t)\right), \tag{2}$$

where

$SE(t)$ represents the savings on electric energy in year t (in kWh),
IE_j, the improvement factor applied to electric energy consumption of equipment class j,
$M_j(t)$ market share in year t for equipment class j,
$E_j(t)$ represents the total electricity consumption of the market segment consumed by equipment class j in year t defined as follows:

$$E(t) = \sum_{j=1}^{m}\left[\sum_{i=1}^{n}\left(\alpha_i(t, x_s)\, E_{i,j}(t)\right)\right] = \sum_{j=1}^{m} E_j(t) , \tag{3}$$

where

m represents the total number of equipment classes,
$E_{i,j}(t)$ represents the electric energy consumption of building i and equipment class j in year t (e.g., in kWh),
$E_j(t)$ represents the electric energy consumption of equipment class j in year t summed over all n buildings (e.g., in kWh).
α_i is a binary variable for building i, which takes values of unity when all conditions of x_s are satisfied; otherwise α_i is zero. For example, if $x_s = (x_1, x_2, x_3) = (1,1,1)$, then $\alpha_i = 1$; otherwise, $\alpha_i = 0$. In other words $\alpha_i = 1$ if building i is a member of the market segment and is zero otherwise. As a result, α_i can be considered a variable indicating membership in the market segment.

Annual Electric Peak Demand Reductions

$$SD(t) = \sum_{j=1}^{m} \left(D_j(t) \cdot ID_j \cdot M_j(t) \right) , \tag{4}$$

where

SD(t) represent the savings of electric peak demand in year *t* (in kW),
ID_j the improvement factor applied to peak electric demand of equipment class *j*.
$D_j(t)$ represents the total electric peak demand of the market segment attributable to equipment class *j* in year *t*.

$$D(t) = \sum_{j=1}^{m} \left[\sum_{i=1}^{n} \left(\alpha_i(t, x_s) \cdot D_{i,j}(t) \right) \right] = \sum_{j=1}^{m} D_j(t) \quad , \tag{5}$$

where
$D_{i,j}$ represents the electric peak demand of building *i* and equipment class *j* in year *t* (e.g., in kW),
D_i represents the electric peak demand of equipment class *j* in year *t* summed over all *n* buildings (e.g., in kW).

Annual Savings on Electricity Expenditures

The impacts on electricity expenditures are defined as yearly savings on expenditures for electricity resulting from electricity savings in year *t* [*CE (t)*] and are given by

$$CE(t) = SE(t)\ PE(t) \text{ , and} \tag{6}$$

The yearly savings on expenditures resulting from peak demand reductions in year *t* [*CD(t)*] are given by

$$CD(t) = SD(t)\ PD(t), \tag{7}$$

where

PE(t) represents the price of electricity projected for year *t*, and
PD(t) represents the demand charge projected for year *t*.

Sources of Data

Although the "perfect" framework is designed to be data driven, with that data being highly granular, we recognize that in many situations only highly aggregated data will be available to analyze the impacts of a product. These data may just be statewide consumption totals by sector or end use. If we assume that the analyst only has "hard" data for annual commercial-building electricity consumption in California, then a set of assumptions must be made to segment the market for the example product from such a highly aggregated number.

Suppose the product being evaluated targets a segment of the air conditioning market characterized by packaged units greater than 10 tons in buildings greater than 50,000 ft^2. Obviously, the energy dimensions of this segment cannot be known immediately from the highly aggregated statewide commercial electricity consumption figure available to the analyst in this example. We start by defining the assumptions needed to whittle the aggregated number to a reasonable value characterizing the segment of interest. First, an informed assumption about the fraction of total commercial-building electricity consumption used for air conditioning should be made based on the best available study. Next, the analyst needs some basis for characterizing the fraction of air-conditioning electricity usage consumed by packaged units. Further basis is required to parse packaged-unit electricity consumption into ton classes. A basis is also needed to determine the fraction of commercial-building electricity consumption in buildings greater than 50,000 ft^2. Finally, to get the complete market opportunity, the analyst needs a basis for determining the proportion of the total market reflected in the specific geographic area of interest.

Examples of market segment determination along a continuum of data availability and data granularity are provided in Kintner-Meyer et al. (2003). The examples span a wide range from scenarios in which highly detailed building stock survey data and actual equipment meter data exists, to cases where only energy consumption data for major end-use are available. It is important to point out that because assumptions are used to replace observed data that may not be available, the degree of introduced error increases. In most impact assessment analyses, detailed energy data and, to an even greater extent peak demand data, do not exist, leaving the analyst with no alternatives but filling the data gaps with appropriate assumptions. The top-down approach should only be used when detailed building stock data are not available. When they are used, all assumptions and supporting information should be documented and included in the reporting of final impact assessment results.

To produce the sample results described below, Pacific Gas and Electric Company's (PG&E) service territory was selected as the example geographic market. We selected PG&E's service territory primarily because high-resolution survey data on commercial end-uses was available in electronic format. In 1996 and 1997, PG&E collected commercial building data using an on-site survey of almost 1,000 commercial customers chosen to represent the population of commercial buildings in the PG&E electric service territory. This survey collected data on the building structures, business operations, equipment types, fuel choices, and operating schedules. While the examples are specific to PG&E's data set, a similar analysis for a particular product could be performed using data from any highly disaggregated commercial end-use database covering any geographic region.

Just having the raw buildings survey data is not sufficient to reliably characterize market segments in energy terms. For each energy end-use potentially affected by the research product, two sets of shares or splits are required to derive market segments in terms of energy metrics. We define the shares as 1) the annual energy end-use factor and 2) as summer peak load ratio. Kintner-Meyer, et al. (2003) provides the full discussion of the need for and use of annual energy end-use factors and the summer peak load ratios by building type. Table 1 exemplifies this data for research products that affect the electricity use of ventilation and cooling equipment in commercial buildings.

Table 1. California Annual Energy End-Use Factor[1] and Peak Load Ratio[2] by Building Type

Building Type	Energy Factor		Peak Load Ratio	
	Ventilation	Cooling	Ventilation	Cooling
Large Offices	0.1319	0.1847	0.1463	0.5093
Restaurants	0.1237	0.1076	0.1405	0.2776
Retail Stores	0.0939	0.1261	0.1624	0.4070
Food Stores	0.0690	0.0559	0.0984	0.2892
Warehouses	0.0590	0.0426	0.1547	0.3973
Schools	0.1185	0.1155	0.1720	0.6345
Colleges	0.1543	0.2263	0.1292	0.4817
Health Care	0.0729	0.2222	0.1446	0.4393
Hotels/Motels	0.0712	0.1867	0.1072	0.5467
Misc.	0.1280	0.2103	0.1230	0.4445

[1] annual energy end-use factor is defined as the fraction of the annual electricity consumption of a particular end-use to total annual electricity consumption for the building.
[2] peak load ratio is defined as the ratio of electric demand of a particular end-use to the total building demand, both at conditions corresponding to the time of the electric power system peak.

Assessment Examples

To demonstrate the user-defined market penetration approach using the logit function and expert judgment, we needed one single product that currently does not have any competitor in the market place. We chose a novel HVAC diagnostics tool for that purpose, which we call "Product 1" throughout this paper. The diagnostics tool applies to the packaged rooftop and central plant HVAC systems (Katipamula, et al. 2003).

To illustrate market penetration under competition with multiple players, we selected two scenarios that demonstrate somewhat different uses of the Peterka model and the impact analysis. The first scenario represents a retrofit case in which the competing products are considered retrofitable accessories to existing HVAC equipment. The two products chosen are: 1) an add-on product (called AFDD1 for this exercise) that is based on Purdue University's vapor compression diagnostics tool (Smith and Braun, 2003) and 2) an add-on product (called AFDD2) that is based on the outdoor air economizer diagnostician developed by Battelle (Katipamula, et al. 1999).

The second scenario illuminates the use of the assessment framework for products that are likely to be deployed in new equipment. We defined a product (called EPRUC for this exercise) that is based on Purdue University's demand-controlled ventilation research (Braun, et al. 2003). We assumed the product would be embedded in the controller of new packaged HVAC units. Comparative market penetration models require a reference technology, which was defined as a representative packaged rooftop HVAC unit as it exists in the current stock - without these demand-controlled ventilation capabilities.

For brevity's sake, we summarize the cost inputs to the Peterka model in Table 2 below. The full derivations of the capital costs and the operation and maintenance costs are provided for each example product in Kintner-Meyer, et al. (2003).

Table 2. Parameters Used for Modeling Market Penetration

Parameter	Units	New Construction		Retrofit		
		Existing HVAC	EPRUC	Existing HVAC	AFDD1	AFDD2
Specific Investment	$/kW	$284.33	$303.67	$0.00	$19.33	$18.20
Specific O&M cost	$/kW / year	$92.78	$85.86	$93.78	$88.23	$89.60
Initial Market Share	Fraction	0.995	0.005	0.990	0.005	0.005

Results

To estimate impacts of the example products, we forecasted the market penetration of each product into its respective market segment using an expert opinion-based logit function for Product 1 and a market penetration approach based on the Peterka model for products AFDD1, AFDD2, and EPRUC.

Figure 2 illustrates market penetration functions expressed in terms of annual and cumulative sales that were estimated for the different product scenarios. The bottom left chart illustrates the model's representation of competition between AFDD1 and AFDD2. The resulting impacts on sales can be seen in the adjacent chart (bottom right). It should be pointed out that the quantitative market penetration results in Figure 2 are illustrations of the kind of results an analyst may obtain. The results are not meant to be used to compare the market penetration approaches.

The cumulative impacts of these scenarios are presented in Figure 3 below. Because the study was developed for the PG&E service territory, the results reflect impacts projected only for that region of California. The cumulative results are presented in terms of the amount of electricity saved (GWh) and the amount of electricity expenditure savings expected to result through 2030. In the case of Product 1, based on hypothetical expert opinion as to the likely penetration function, the product is likely to result in annual savings of about 120 GWh in electricity consumption, 50 MW of peak demand, and $18 million (constant 2001 dollars) in electricity expenditures by 2030. Over the analysis period, these annual impacts translate to cumulative savings of about 2,400 GWh and $340 million (2001) of electricity expenditures.

In the retrofit scenario, the AFDD1 and AFDD2 products are in competition with each other for application as a retrofit to existing packaged 25-ton HVAC units. The Peterka model results indicate that the products successfully penetrate the existing packaged HVAC market and reach saturation by 2024. The AFDD1 product out competes the AFDD2 product by offering a relatively higher performance improvement per incremental capital investment.

In the new-equipment scenario, the EPRUC-equipped units compete against conventional new 25-ton packaged HVAC units. The EPRUC achieves only slight penetration into the new equipment market compared to the AFDD1 or AFDD2 products sold as "add-ons". The difference in impacts can be traced to the magnitude of capital investment required for EPRUC-equipped new units compared to buying a retrofit box. Lower improvement factors available with the EPRUC product also contribute to lower penetration estimates.

Figure 2. Market Penetration Estimates of the Alternative Product Scenarios

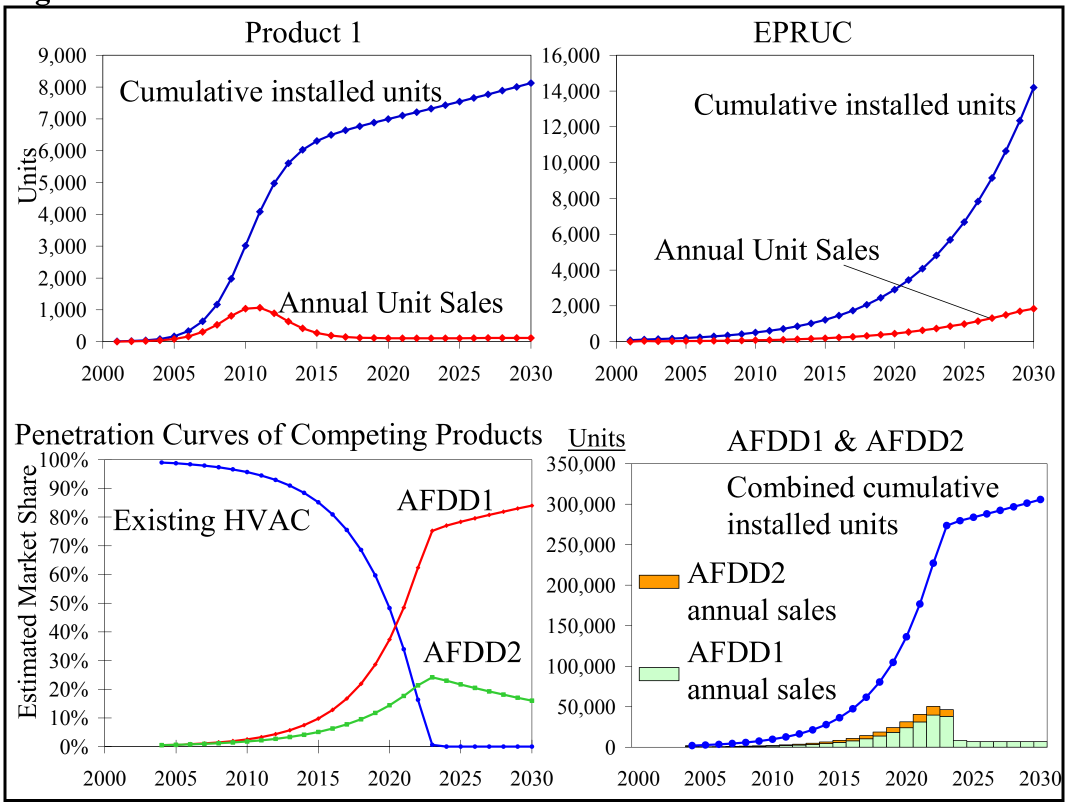
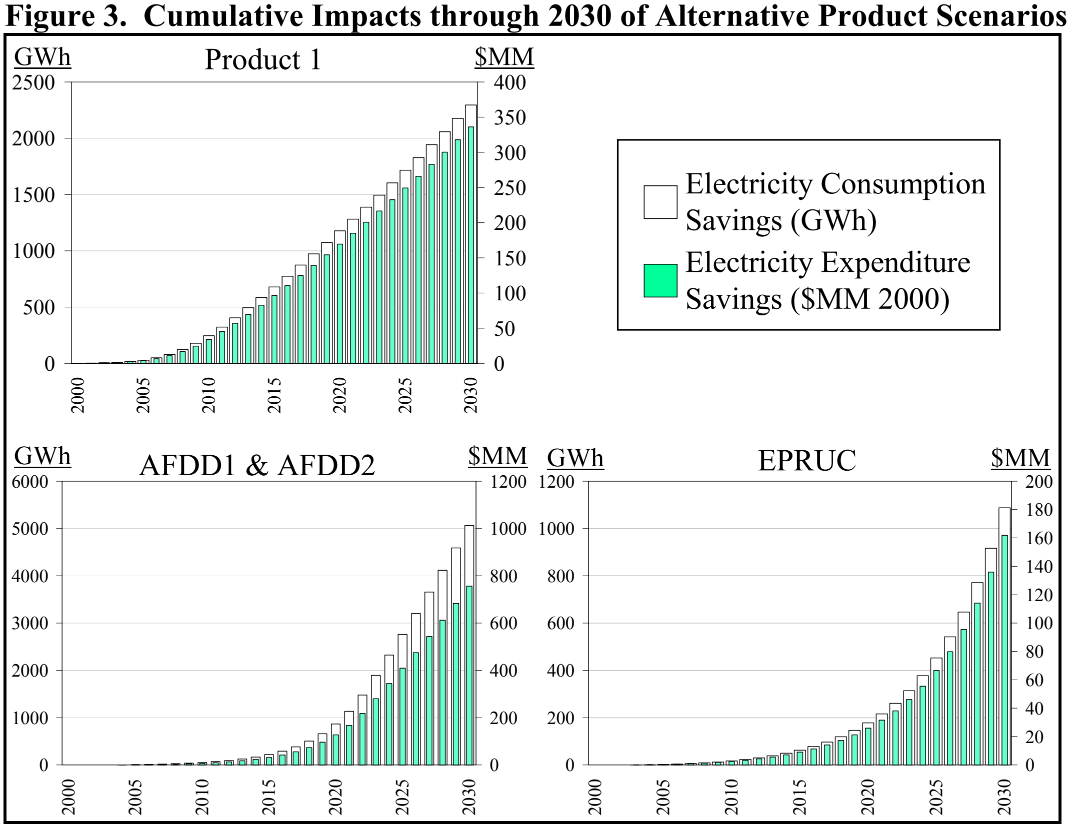


Figure 3. Cumulative Impacts through 2030 of Alternative Product Scenarios



Model Limitations and Caveats

Several key parameters affect the ability of the modeling framework to provide reasonable estimates in the judgment of analysts (Kintner-Meyer, et al. 2003). These include the electricity price and associated demand charges, incremental costs of the products modeled, performance improvement factors, and assumptions about product operations and market segment size. In addition, several parameters affect the results generated by the penetration algorithms, including the user-defined parameters defined earlier, operation costs, and the initial market share.

Analysts must be aware of the caveats that apply to market penetration modeling. The product development cycle in a market economy seeks to correct perceived inefficiencies as they become apparent. This happens by customers demanding new and better products (demand pull) or by technology development that makes customers aware of new and better products (technology push). This process is continual and dynamic; however, market penetration models typically consider new product competition in isolation from this process. (Bayus, et al. 2000; Rogers, E. 1983). For example, we have demonstrated scenarios affecting the packaged HVAC market. The model does not consider that several other product development efforts may be attempting to compete for the same market segment with alternative products to those modeled in our examples.

These example penetration functions imply that perhaps the energy cost savings offered by some new products may cause a shift from an existing product to a new product, and that in out years of the forecast, penetration will remain stable. Out-year stability implied by visually inspecting the penetration functions cannot be assumed. Market dynamics will cause subsequent products to be developed and compete for the same market segments modeled in these scenarios. Thus, the models become valuable for illustrating a product's market potential, but should not suggest that a product will remain at its maximum market share indefinitely. Rather, as more efficient products are developed, it seems reasonable to assume that future products competing for the same market segment will likely be more efficient than their predecessor products.

It should also be mentioned that determining the baseline for the impact assessment is non-trivial. Naturally occurring energy efficiency improvements caused by turn-over of old to newer equipment tend to reduce the overall savings potential of the technology being analyzed. The analyst needs to be cautious in setting an appropriate forecasting horizon that recognizes when the energy efficiency advantages of the technology to be assessed vanishes or approaches an insignificant improvement over the existing stock that will have been improved by natural occurrences. Furthermore, energy efficiency standards that become effective at some future time impose discontinuities in the naturally occurring energy efficiency improvement process that may render the new technology ineffective.

Discussion

The technical potential of an energy saving product should not be confused with the likely actual impact in the market. Technical potential is usually defined as the total energy savings possible when a product is used in place of another less efficient one or applied in a way that increases the efficiency of an existing product. The casual analyst might multiply the value of potential savings per unit by the total number of units in use or a projection of number of units at some future time, and claim the result as an estimate of the potential impact of the product.

This sort of estimate represents a maximum potential, but it is an unrealizable absolute maximum energy savings impact achievable only if the product were to reach 100% penetration of the market. Such large penetration is highly unlikely given the several compounding factors, such as competition from other new products during the life-cycle of the subject product and market force changes caused by new energy standards and other break-through technologies.

Even under the best conditions, as the penetration curves in the Results section of this paper illustrate, many years are required to achieve even small fractional penetration. For example, in Figure 2, 10 years after initial introduction, neither of the two new products (AFDD1 and AFDD2) has penetrated 10% of the market. Funders of research, policy makers, and developers alike should realize that, most often, many years will pass before an investment in development will provide significant impacts. Expectations should not be unreasonably set based on wishes for what "should" happen, given an estimate of technical potential.

Pubic policies and programs can, however, create opportunities to impact the rate of penetration of beneficial technologies. The assumed initial market share at the time a product is introduced has a particularly pronounced influence on the rate at which a product penetrates the market. Products with larger initial market shares generally capture market share faster and reach their peak rate of penetration years sooner than products with smaller initial market shares. As a result, programs and policies that "create' initial market share can have particularly important impacts on the success of an energy savings product in the market. These policies and programs include technology/product demonstrations, market transformation activities, utility programs that introduce new energy-saving technology, as well as tax and other direct subsidies that reduce costs of energy-saving and load-management products.

Conclusions

As with any modeling and analysis framework, responsible application of the tools and approaches introduced here remains the responsibility of the analyst using the assessment methodology. Because of the transparency of assumptions made, the users of this assessment framework can check and validate projection assumptions, data, calculations, or estimates for agreement with citable sources, industry experience, and analytical intuition.

The assessment methodology presented here allows the analyst to use market intelligence to improve estimates of probable technology impacts. If marketplace competition exists, as in our sample cases AFDD1/AFDD2 and EPRUC, the Peterka model provides an explicit approach to include these market interactions. Alternatively, if a novel technology is introduced into the market with no known competition, or this competition is difficult to quantify, then the expert-opinion-based logit function can be applied to estimate future energy and demand savings, as in our sample case of Product 1. Each of these approaches has a role within an assessment methodology that is employed to evaluate a broad and diverse energy efficiency R&D portfolio.

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