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Program Design Analysis using BEopt Building Energy Optimization Software: Defining a Technology Pathway Leading to New Homes with Zero Peak Cooling Demand

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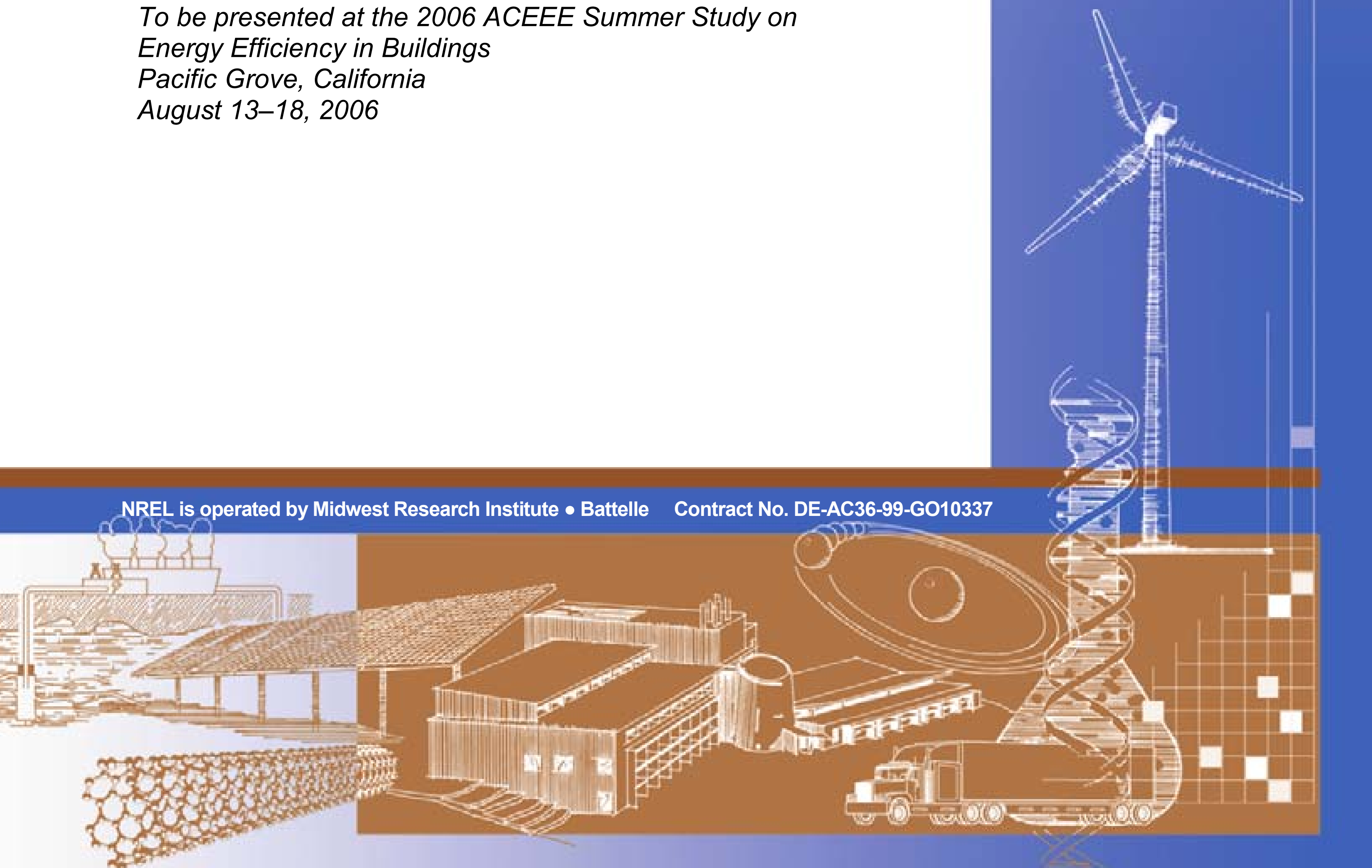

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Program Design Analysis using BEopt Building Energy Optimization Software: Defining a Technology Pathway Leading to New Homes with Zero Peak Cooling Demand

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ABSTRACT

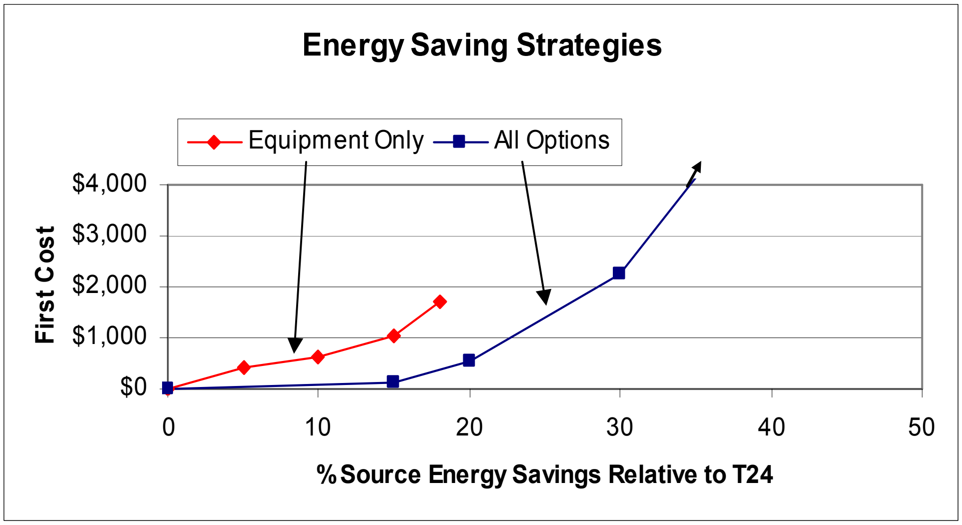
An optimization method based on the evaluation of a broad range of different combinations of specific energy efficiency and renewable-energy options is used to determine the least-cost pathway to the development of new homes with zero peak cooling demand. The optimization approach conducts a sequential search of a large number of possible option combinations and uses the most cost-effective alternatives to generate a least-cost curve to achieve home-performance levels ranging from a Title 24-compliant home to a home that uses zero net source energy on an annual basis. By evaluating peak cooling load reductions on the least-cost curve, it is then possible to determine the most cost-effective combination of energy efficiency and renewable-energy options that both maximize annual energy savings and minimize peak-cooling demand.

Introduction

A growing number of "beyond-code" residential energy programs in the United States maximize whole-house energy savings by targeting all residential end uses rather than focusing energy-saving strategies on specific building components. Examples of programs that target whole-building energy savings include the Sacramento Municipal Utility District (SMUD) Zero Energy Home (ZEH) Program, U.S. Department of Energy (DOE) Building America Program, and California Energy Commission's (CEC) Zero Energy New Homes (ZENH) program. Figure 1 compares the first costs of two different approaches to increasing source energy savings beyond Title 24 in a 2,592-ft^2 two-story home in Sacramento. The upper cost curve in Figure 1 represents costs for a program that only targets space-conditioning equipment options. The lower cost curve represents costs for a program that includes all energy-savings options. The benefits of the whole-buildings approach are clear from comparing the costs and energy savings associated with the two different curves. The program that only targets equipment options is limited to maximum source energy savings of about 18% relative to Title 24 and has first costs that are significantly higher than the program that is based on using all available energy-saving options.

Programs that target whole-building energy savings are more cost effective for program providers and participants, but they also provide many challenges. One of these is the challenge of developing a consistent method for comparing the costs, energy savings, and interactions between the large number of different combinations of energy-savings options that can potentially be used to achieve whole-building energy savings. Researchers at the National Renewable Energy Laboratory (NREL) have developed the BEopt analysis method as one approach to solving this analysis problem. The results from the BEopt analysis method provide a starting point for development of multi-year program targets that can then be updated over time based on actual program results.

Figure 1. Comparison of Energy Saving Strategies for a Two-Story Home in Sacramento



Summer cooling loads are a significant contributor to high energy generation and transmission and distribution (T&D) costs for California utilities. Significant incentives have been added to the Title 24 Code to encourage the development of construction approaches that minimize peak cooling loads in new homes (Heschong Mahone Group 2002, Pacific Gas and Electric 2002). The cost of building new power plants and T&D systems can be significantly reduced if new homes are designed with zero peak cooling loads. The objective of this paper is to evaluate the most cost-effective technology pathway for a program that has the goal of building new homes that minimize peak cooling loads.

Technical Approach

Christensen, Horowitz & Barker (2004) developed an analysis method (BEopt) to determine the least-cost path to Zero Net Energy (ZNE) homes, based on evaluating the marginal costs of different combinations of energy efficiency and renewable-energy options. This method has recently been applied to determine the most cost-effective approaches to achieve the near-term and long-term performance targets for the DOE Building America Program (Anderson, Christensen & Horowitz 2006)

The BEopt analysis method uses an efficient sequential search-optimization technique to find optimal and near-optimal combinations of discrete energy efficiency options. The development of this analysis method was influenced by several factors. First, the method identifies intermediate optimal points all along the path of interest (i.e., minimum-cost building designs at different target energy-savings levels), not just the global optimum or the ZNE optimum. Second, the method allows discrete rather than continuous building options to be evaluated, reflecting realistic construction options. Third, an additional benefit of the search strategy is the identification of near-optimal alternative designs along the path, allowing for substitution of essentially equivalent solutions based on builder or contractor preferences.

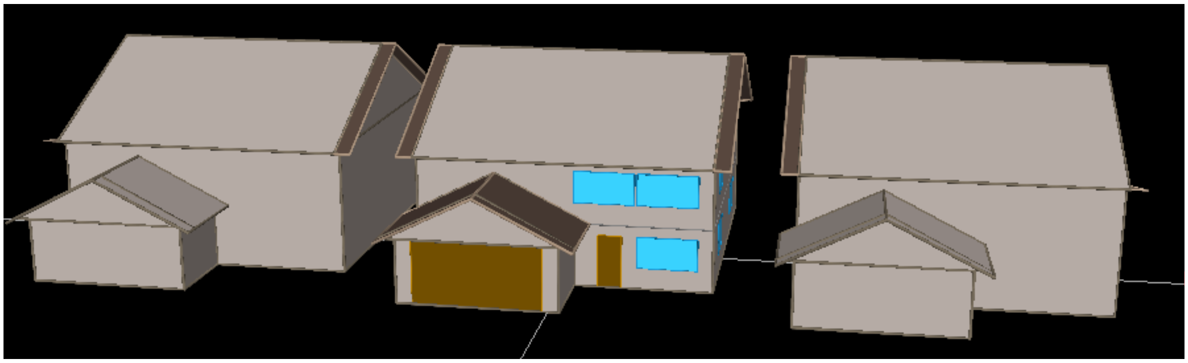
The sequential-search approach used by the analysis method involves searching all categories (wall type, ceiling type, window glass type, HVAC type, etc.) for the most cost-effective combination at each sequential point along the path to ZNE. Starting with the base-case building, simulations are performed to evaluate all available options for improvement (one at a time) in the building envelope and equipment. Based on the results, the most cost-effective combination is selected as an optimal point on the path and put into a new building description. The process is repeated. At each step, the marginal cost of saved energy is calculated and compared with the cost of PV energy. From the point where further improvement in the building envelope or equipment has a higher marginal cost, the building design is held constant, and PV capacity is increased to reach ZNE.

For the purposes of the current study, the BEopt method is applied to a two-story home in Sacramento, California, to determine the least-cost path to maximize annual source energy savings and minimize peak cooling demand. A home with a zero peak cooling demand is achieved by first determining the most cost-effective combination of envelope and equipment measures required to minimize source energy use. When the marginal cost reductions in source energy use through the use of energy efficiency measures is equivalent to the cost of using a grid-connected residential PV system, further investments in energy efficiency are stopped, and residential PV is added to the home until the remaining electric demand for cooling is directly offset by the site electricity provided by the PV system. Representative construction costs and utility rates were used in the current study to demonstrate the use of the BEopt analysis method to define technology pathways to specific energy-performance goals. All of the cost, performance, building-geometry, and building-operation inputs used in the present study can be modified as needed to reflect specific building types, construction costs, and utility rates.

Building Characteristics Considered in This Study

A simple two-story 2,592-ft^2 home with an attached two-car garage was used for this study (Figure 2). The home has 1-ft eaves and a slab foundation. Window area was assumed to be 18% of floor area and was equally distributed among outside walls. Window distribution is a user input to the analysis and can be modified to reflect specific home designs as needed. The study was limited to one orientation (back facing west), allowing full exposure of the windows on the back of the home to afternoon sun. Adjacent homes 10 ft to the north and south provide shading of sidewalls. The energy options considered in the study include space-conditioning systems, envelope systems, hot-water systems (including tankless and solar hot water), lighting systems, major appliances, and grid-connected residential PV. No specific options that address miscellaneous electric loads other than major appliances were included in the study. The homeowner costs calculated in the study assume a 30-year mortgage at a 7% interest rate with a 3% general inflation rate and a 5% real discount rate. The net present value of replacements for options with lifetimes less than 30 years were included in option costs. The specific descriptions of the energy efficiency and renewable-energy options considered in this study cannot be included within the space limitation for this paper and are summarized in the appendix of Anderson et al. 2004.

Figure 2. Simple House Geometry Used in Current Study



Occupancy/Operational Assumptions

The occupancy and operational assumptions used in the study are defined in the Building America Research Benchmark (Hendron 2005) and include time-of-day profiles for occupancy, appliance and plug loads, lighting, domestic hot-water use, ventilation, and thermostat settings.

Base-Case Building Characteristics

Incremental energy savings and incremental home costs are calculated relative to a base-case building that meets Title 24 requirements for Sacramento (California climate zone 12; personal communication, Steve Vang). The base-case building includes low-leakage tested ducts with R-4.2 insulation, low solar-heat-gain windows, R-13 walls, R-38 ceiling insulation, and a SEER 13 air-conditioning (AC) system.

Cost Assumptions

Each option has an assumed first cost and lifetime. Costs used in the analysis represent retail costs and include national average estimated costs for hardware, installation labor, overhead, and profit. Construction costs (wall insulation, ceiling insulation, foundation insulation, etc.) are typically based on national average cost data (R. S. Means 1999). Window and HVAC costs are based on quotes from manufacturers' distributors. Appliance costs are based on manufacturers' suggested retail prices.

Building construction options (wall insulation, ceiling insulation, foundation insulation, windows, etc.) are assumed to have 30-year lifetimes. Equipment and appliance options typically have 10- or 15-year lifetimes. Lifetimes for lighting options (incandescent and compact fluorescent lamps) are modeled based on cumulative hours of use.

Utility costs are assumed to escalate at the rate of inflation (i.e., to be constant in real terms). The onsite power option used for this study was a residential PV system with an installed cost of \$7.50 per peak Watt_{DC}, including present value of future operation and maintenance (O&M) costs. Natural gas is assumed to have an average cost of \$1/Therm. Electricity was assumed to have an average cost of \$0.127/kWh. The home is assumed to have a gas water heater (or solar hot water heater with gas backup), a gas furnace, a gas clothes dryer, and a gas stove. The impact of long-term increases in the cost of energy was not considered in the current study. All cost assumptions are user inputs that can be modified to reflect actual costs in specific projects.

The cost estimates used in this study do not include the initial costs required to re-engineer home designs,[1] state and local financial incentives and rebates, or other builder costs, such as warranty and call-back costs. All of these additional cost factors may have a significant impact on builder business decisions related to construction of new home designs and must be considered as part of the design of programs aimed at increasing the construction of high-performance homes.

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[1] Builder re-engineering costs include costs associated with renegotiating relationships with suppliers and contractors, costs required to advertise new home features, technical support required to pass code review, costs for third-party inspections, and costs for contractor training. These costs are largest for early adopters and market leaders who are among the first to try new systems and are proportionally smaller for best-practice builders and standard practice builders who wait before adopting new systems.

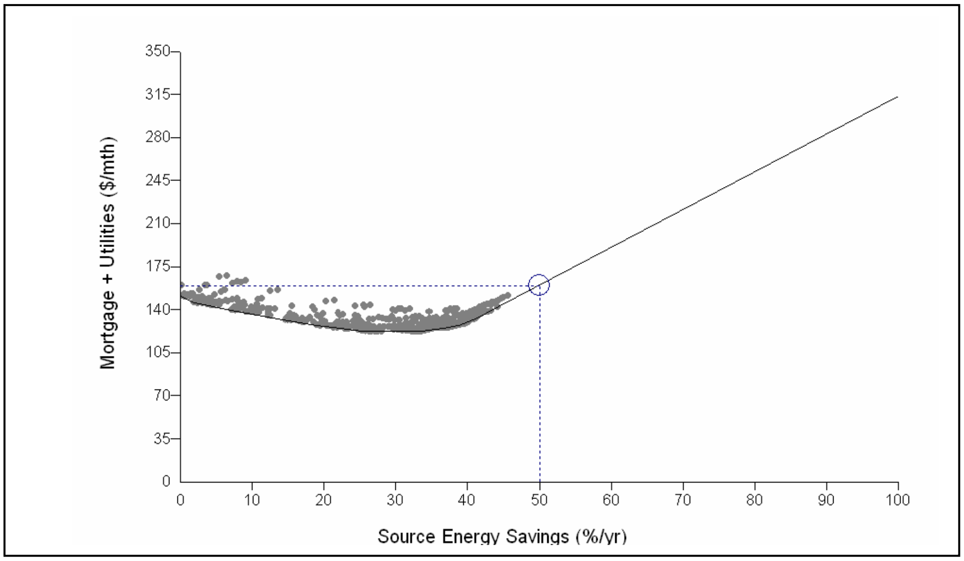
Analysis Results

The least-cost curve is shown as a function of source energy savings in Figure 3.[2] At zero source energy savings, the cost on the curve at the vertical axis represents the annual utility bill for a homeowner with a Title 24 home. Each point in Figure 3 represents a different combination of equipment and envelope options for the home. The BEopt method conducts an annual energy simulation for a large number of possible option combinations in the vicinity of the least-cost curve. The least-cost curve represents the lower bound of these combinations of options. One of the benefits of the BEopt analysis method is the ability to identify a large number of option combinations represented by the points nearest the least-cost curve that have nearly equivalent cost and performance.

The marginal cost of increased energy efficiency is equal to the marginal cost of electricity from residential PV when source energy savings reach about 44%. The straight line that begins at source energy savings of 44% represents the cost of using a net-metered, grid-connected PV system to meet remaining home energy needs. The neutral cost point where total energy-related homeowner costs for a high-performance home are equal to the initial utility costs for a Title 24 home occurs at source energy savings of about 50%.

The first costs associated with achieving different levels of source-energy savings on the least-cost curve are shown in Figure 4. The data shown in Figure 4 is the same as the lower curve in Figure 1 but has been expanded to a broader range of source-energy savings. A home with 40% in annual source-energy savings relative to Title 24 increases first costs by $5,000, a 50% home increases costs by $15,000, and a 60% home increases costs by $25,000. If the base home price for the Title 24 home is $500,000, the corresponding fractional increases in home cost required to achieve these higher performance levels are 1%, 3%, and 5%.

Figure 3. Least-cost Curve for a Two-story, 2,592-ft^2 Home in Sacramento



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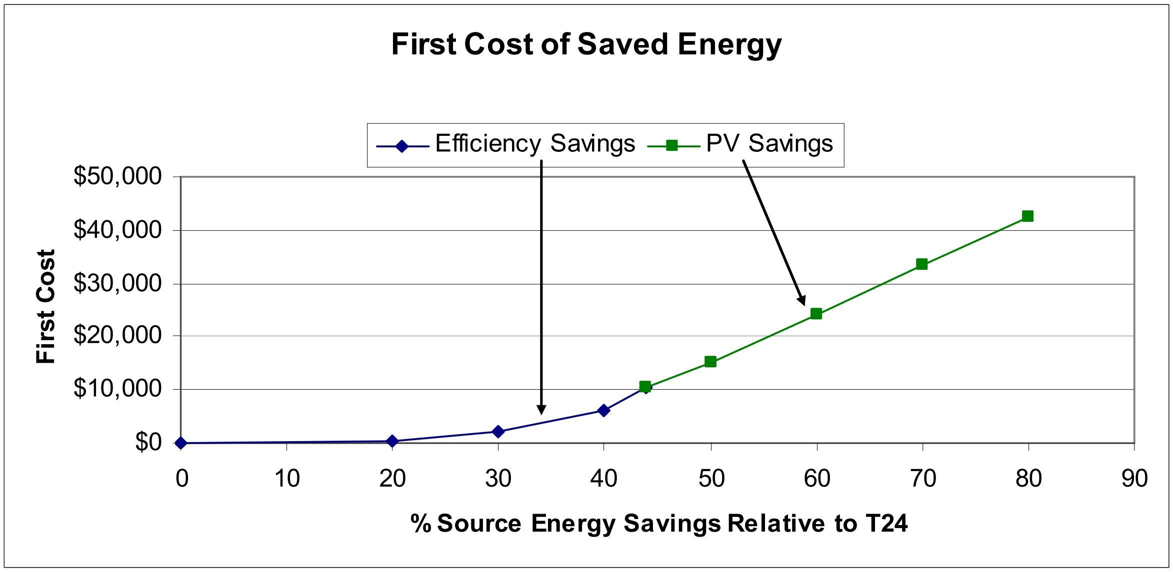
[2] To provide a consistent basis of comparison, source energy savings will be used as the metric for the x-axis throughout this paper.

Figure 4. Incremental First Costs Associated with Achieving Different Annual Source-Energy Saving Levels



The average 30-year cost of site energy savings are shown as a function of source energy-savings level in Figure 5. The first cost required to achieve each savings level was divided by the total site energy savings for gas and electric end uses for the 30-year period of the current study to determine the average costs shown in Figure 5. The average cost of saved energy compares favorably with current residential energy costs out to a source energy-savings level of about 50%-60%. The average cost of electricity provided by PV is shown in Figure 6 and is about $0.17/kWh.

Figure 5. Average Cost of Total Site Energy Savings

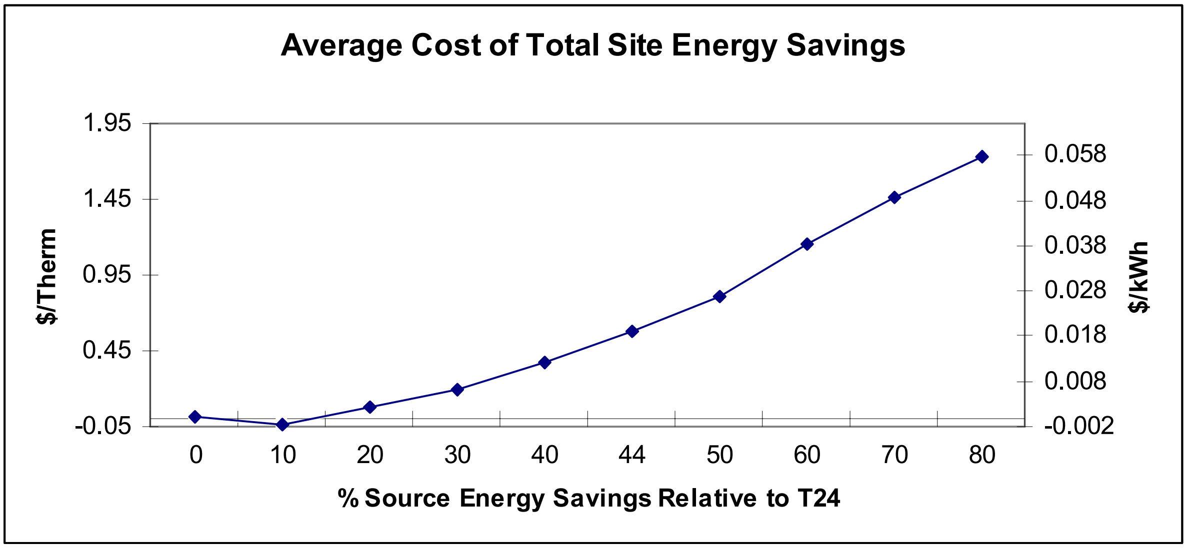
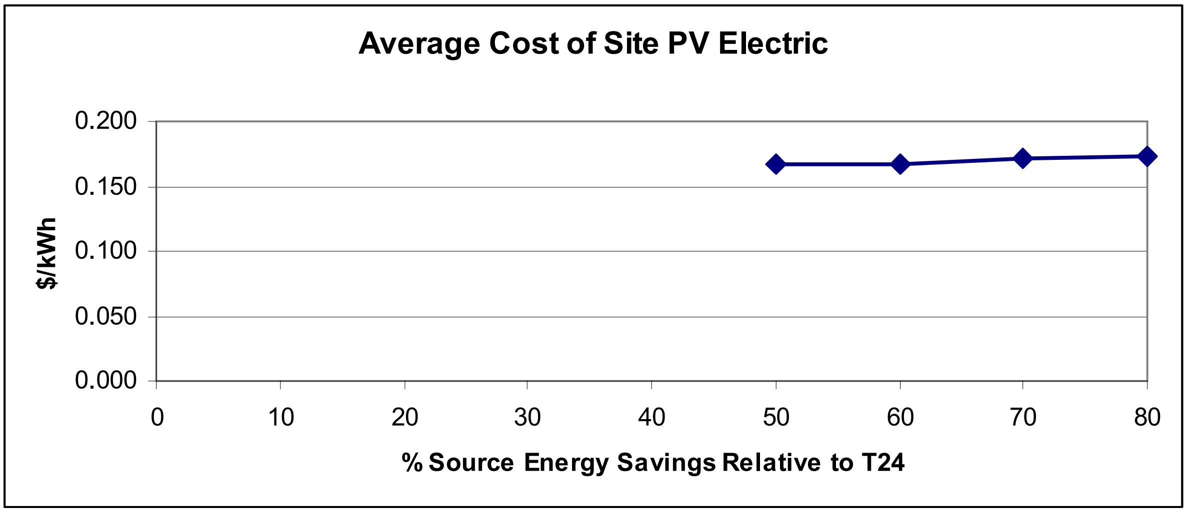
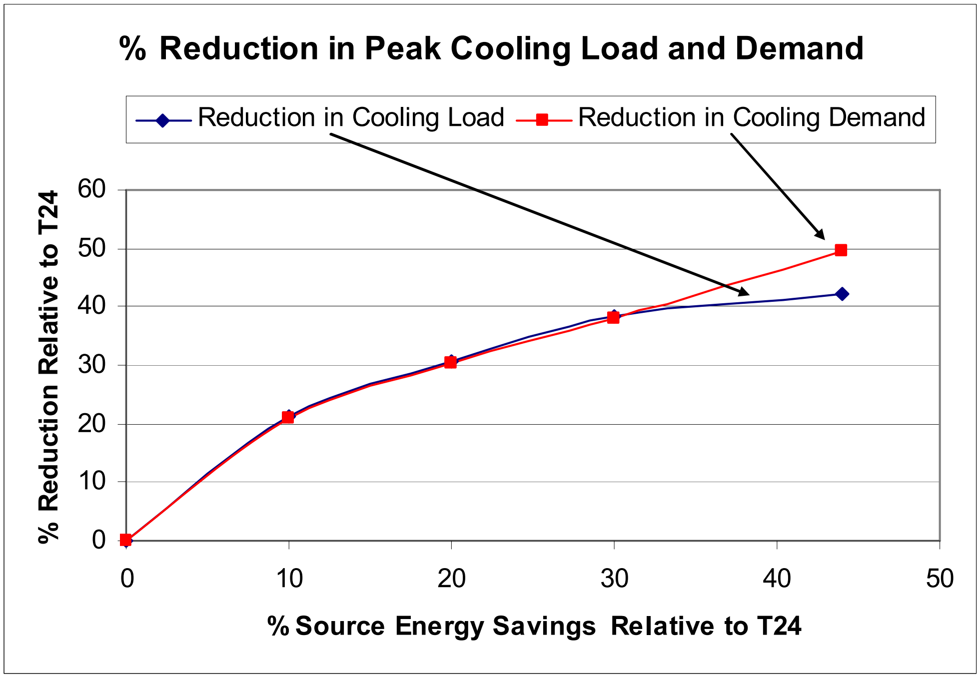


Figure 6. Average Cost of Site PV Electric



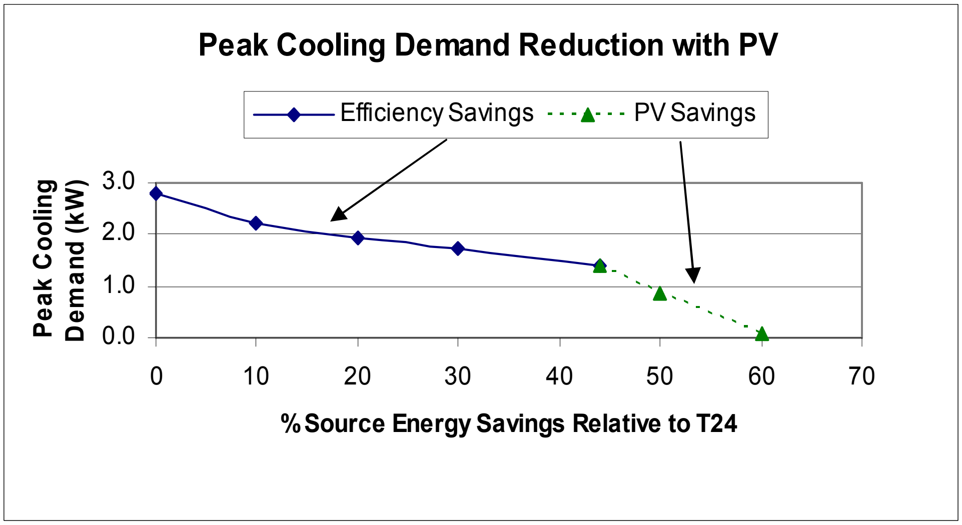
Changes in peak cooling loads and peak cooling demand are shown as a function of source energy savings in Figure 7. Improvements in home energy efficiency reduce peak cooling loads by over 40% (lower curve in Figure 7) and peak cooling demand by 50% (upper curve in Figure 6). The additional reduction in demand relative to loads is the result of the increase of AC SEER from 13 to 15 at the 44% source energy-savings level. In the current study, which assumes installed PV costs of \$7.50/Watt$_{ppc}$, the marginal cost of electric savings from PV is less than the marginal cost of electric savings from high-SEER AC systems for source-energy savings levels greater than 44%.

Figure 7. Impact of Energy Efficiency Improvements on Peak Cooling Loads and Peak Cooling Demand



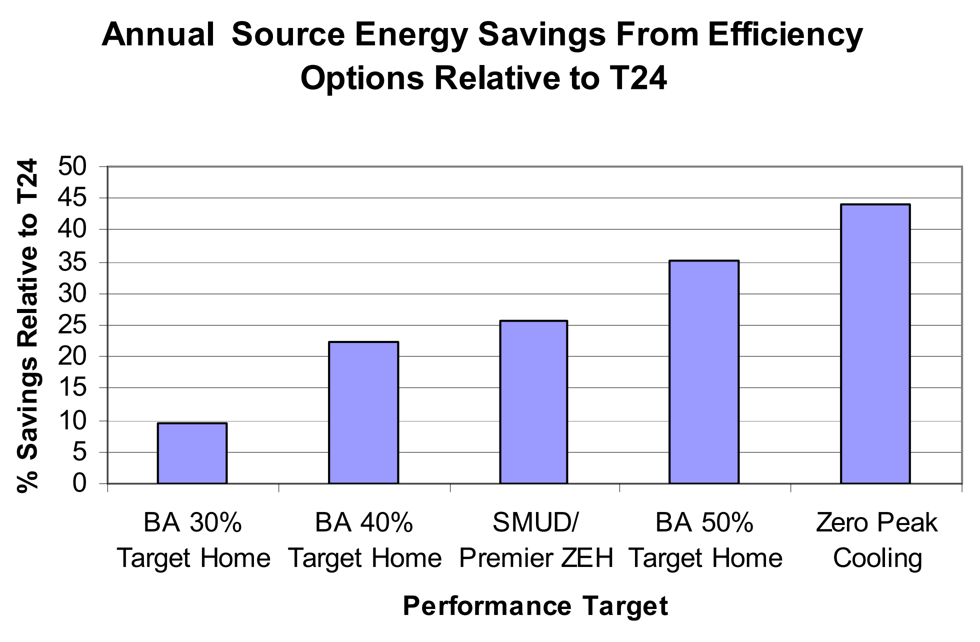
Reductions in peak-cooling demand in dimensional units (kW) resulting from the combination of energy efficiency and PV are shown in Figure 8. The nominal EER of the SEER 13 AC system was assumed to be 11 in Figure 8. At the 60% savings level, a 2-kWp$_{DC}$ PV array with 25% derate factor provides the 1.5 kW required to meet peak cooling demand.

Figure 8. Impact of Energy Efficiency and PV on Peak Cooling Demand



The relative efficiencies of different new residential building program targets are shown in Figure 9. The relative savings shown in Figure 9 do not include the additional source energy savings that occur when PV systems are added to the homes. Building America's near-term national research targets are referenced to a fixed benchmark that represents the average

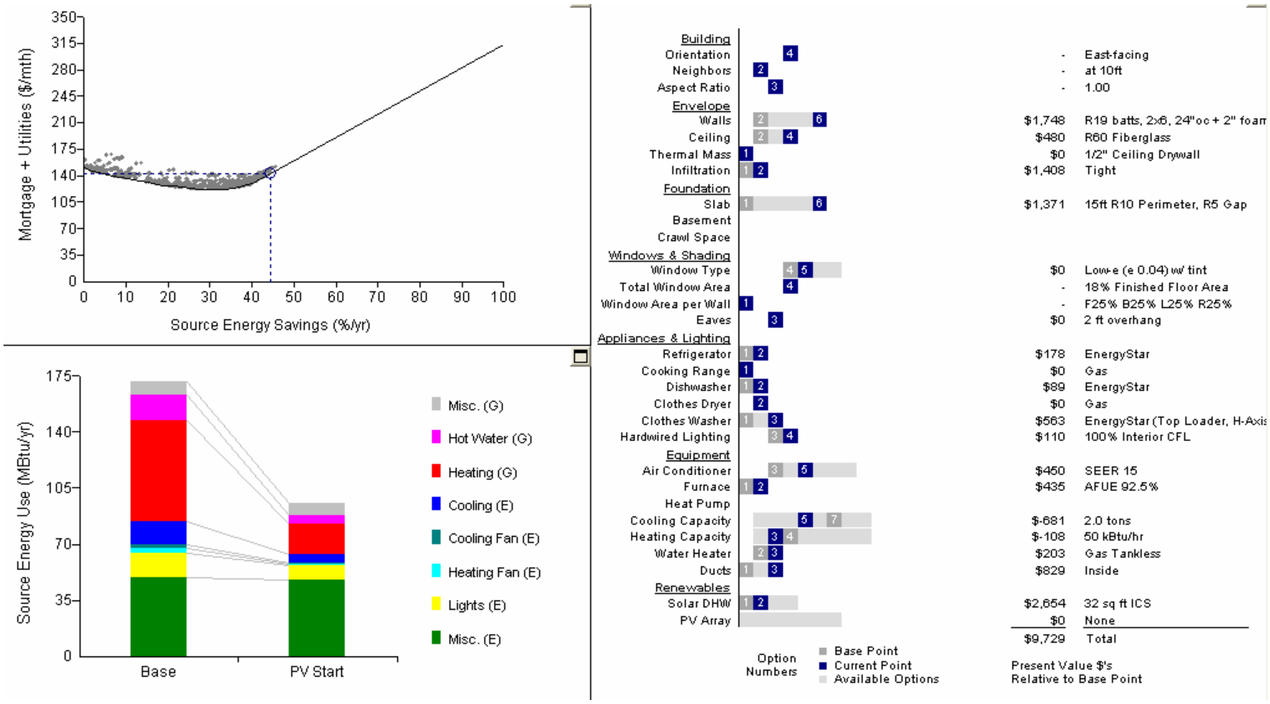
Figure 9. Comparison of Annual Source Energy Savings without PV



performance of 1990s homes and provide efficiency savings ranging from 10%-35% relative to 2005 T24. SMUD's Premier Homes project provides source energy savings of about 25% relative to 2005 T24 for the two-story home considered in the current study when PV savings are not included.[3]

The distribution of annual energy end uses in the home at the point (44% savings relative to T24) where the incremental cost of additional energy efficiency savings are equal to the cost of PV is shown in Figure 10. The right-hand side of Figure 10 also includes a summary of the options used to increase the efficiency of the home relative to the base Title 24 home.

Figure 10. Distribution of Annual Energy End Uses at the 44% Source Energy-savings Level



	Option Numbers		
Building			
Orientation	4	-	East-facing
Neighbors	2	-	at 10ft
Aspect Ratio	3	-	1.00
Envelope			
Walls	2, 6	$1,748	R19 batts, 2x6, 24"oc + 2" foam
Ceiling	2, 4	$480	R60 Fiberglass
Thermal Mass	1	$0	1/2" Ceiling Drywall
Infiltration	1, 2	$1,408	Tight
Foundation			
Slab	1, 6	$1,371	15ft R10 Perimeter, R5 Gap
Basement			
Crawl Space			
Windows & Shading			
Window Type	4, 5	$0	Low-e (e 0.04) w/ tint
Total Window Area	4	-	18% Finished Floor Area
Window Area per Wall	1	-	F25% B25% L25% R25%
Eaves	3	$0	2 ft overhang
Appliances & Lighting			
Refrigerator	1, 2	$178	EnergyStar
Cooking Range	1	$0	Gas
Dishwasher	1, 2	$89	EnergyStar
Clothes Dryer	2	$0	Gas
Clothes Washer	1, 3	$563	EnergyStar (Top Loader, H-Axis
Hardwired Lighting	3, 4	$110	100% Interior CFL
Equipment			
Air Conditioner	3, 5	$450	SEER 15
Furnace	1, 2	$435	AFUE 92.5%
Heat Pump			
Cooling Capacity	5, 7	$-681	2.0 tons
Heating Capacity	3, 4	$-108	50 kBtu/hr
Water Heater	2, 3	$203	Gas Tankless
Ducts	1, 3	$829	Inside
Renewables			
Solar DHW	1, 2	$2,654	32 sq ft ICS
PV Array		$0	None
		$9,729	Total

Present Value $'s Relative to Base Point

In Figure 11[4], the cooling electric demand for the Title 24 reference house is compared to the house with 44% annual source energy savings relative to Title 24 for a peak cooling day with a thermostat set point of 76°F. Even without added PV, the energy efficiency options that have been implemented in the 44% house reduce peak cooling demand by about 1.5 kW.

In addition to the reductions in peak cooling demand shown in Figure 11, the energy efficiency upgrades in the 44% house also reduce total annual heating energy use by 70% and annual cooling energy use by 60% (Figure 12).

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[3] SMUD's Premier Homes Project was originally targeted relative to 2002 T24. Requirements for 2005 T24 are about 15% more stringent than 2002.

[4] Figures 11, 13 and 14 show electric cooling demand only. Additional miscellaneous electric demand totaling about 1kW are not shown in these figures.

Figure 11. Comparison of Cooling Demand without PV

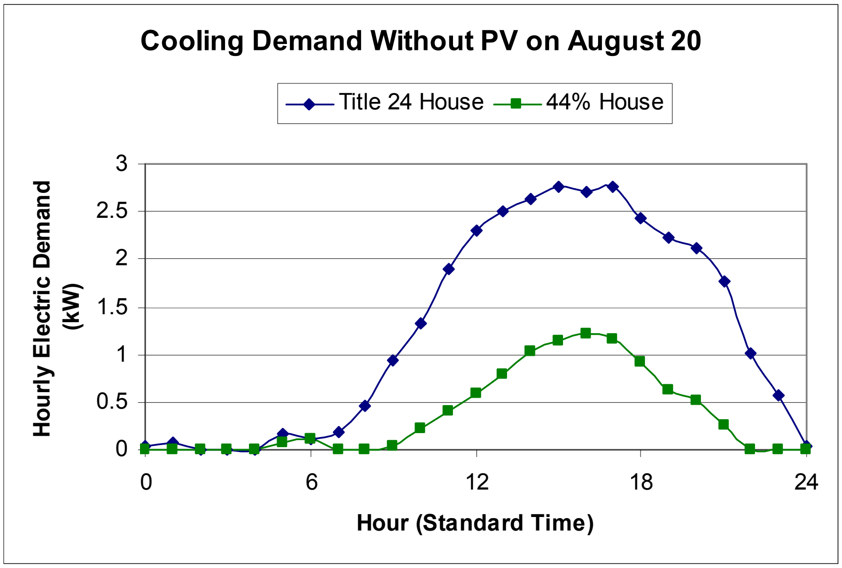
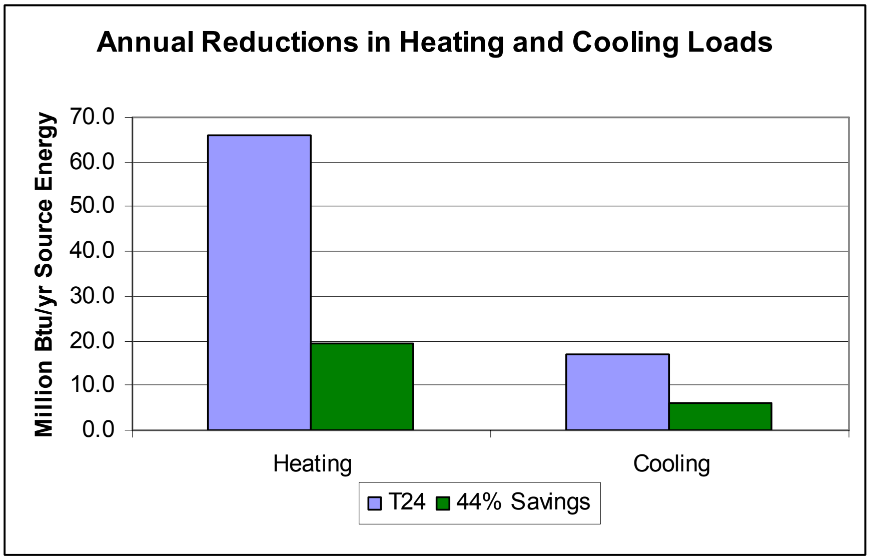
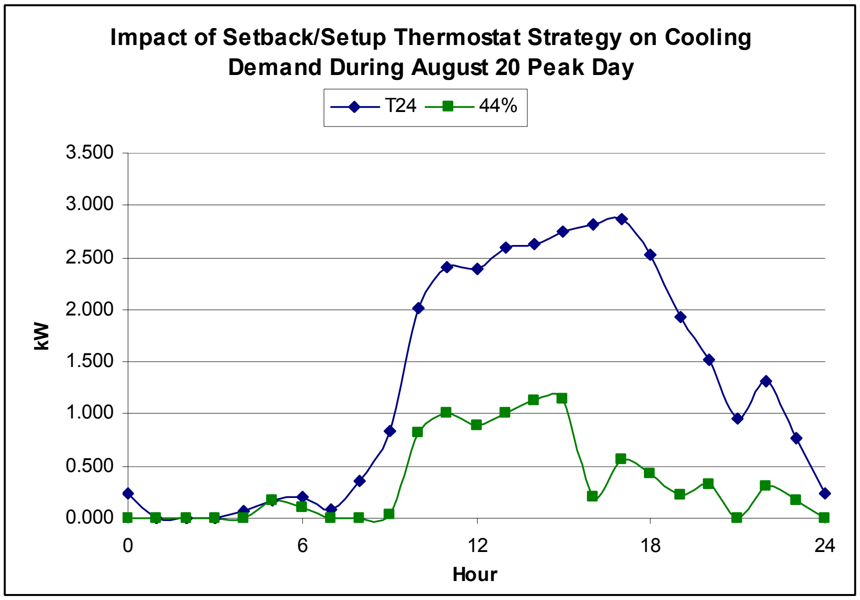


Figure 12. Reduction in Annual Heating and Cooling Source Energy Use without PV



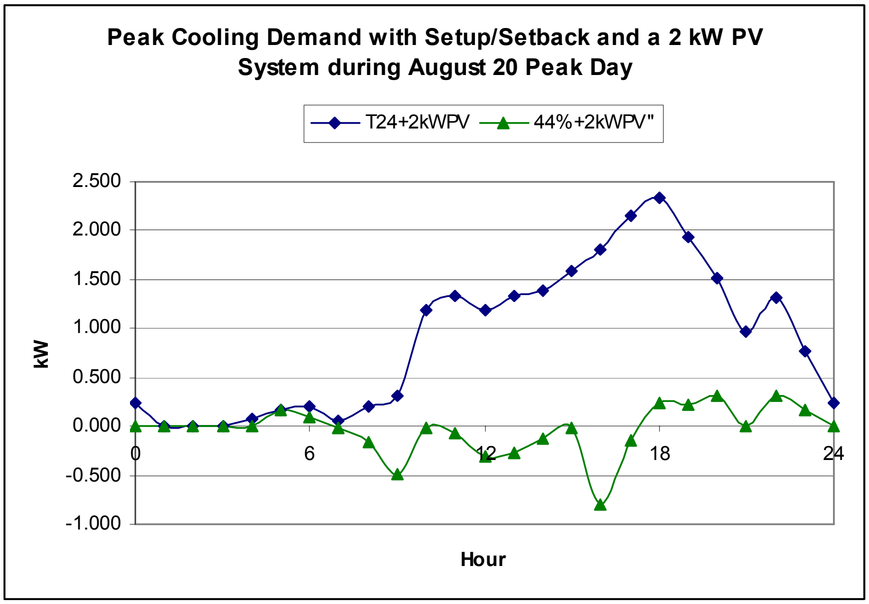
Because of the large reduction in the cooling load of the 44% house, a simple thermostat setback and set-up strategy can have a significant impact on cooling demand in the high-performance home. For the cooling demand results shown in Figure 13, the cooling set point was set to be 76°F from 10 pm to 10 am. The set point was reduced from 76°F to 72°F from 10 a.m. to 4 p.m. and then increased from 72°F to 78°F from 4 p.m. to 10 p.m. Pre-cooling strategies have previously been shown to be cost effective alternatives for commercial buildings (Keeney and Braun 1997). This simple strategy shifts the cooling peak in the 44% house back from late afternoon to mid-morning (lower curve in Figure 13). The same strategy also provides a slight shift in the T24 house, but is insufficient to reduce the late afternoon peak cooling demand (see upper curve in Figure 13).

Figure 13. Thermostat Setback and Setup Significantly Reduce Peak Cooling Demand in the 44% House



The impact of adding a west-facing 2-kWp$_{DC}$ PV system in combination with a thermostat setback and setup strategy is shown in Figure 14. The net impact of the PV system (in combination with energy efficiency measures and the thermostat setback/setup strategy) is to reduce peak cooling demand to nearly zero throughout most of the day in the 44% house (lower curve in Figure 14). The 2-kW PV system reduces the peak-cooling demand in the T24 house in the late morning and early afternoon, but has little impact on the late afternoon peak (upper curve in Figure 14).

Figure 14. A 2-kW PV System has Little Impact on Peak Cooling Load in the T24 House



As can be seen in Figures 11 through 14, the efficiency savings provided by programs with whole-building energy targets provide significant benefits to utilities and consumers and are also important enablers of other advanced technologies and load-control strategies. By maximizing the investment in energy efficiency options before making investments in advanced options like PV, the size and, therefore, the cost of the investment in the advanced option is minimized. A 4-kWpDC array at a cost of $30,000 would be required to achieve a zero peak cooling demand home if no additional investments in energy efficiency beyond Title 24 were made. Not only would a PV-only approach cost more than the optimum found using the BEopt analysis method ($30,000 vs. $25,000), it would also provide significantly lower aggregate peak and off-peak energy savings than the integrated energy efficiency and renewable-energy approach that has been evaluated in the current paper.

Conclusions

The BEopt analysis method has been used to evaluate the costs and benefits of different combinations of energy efficiency and renewable-energy options targeting the development of homes with zero peak cooling demand. The results indicate that it is possible to build a 2,592-ft^2 home in Sacramento at an incremental cost of about 5% relative to a standard Title 24 home that will achieve zero peak cooling demand, reduce total annual heating energy use by 70%, reduce annual cooling energy use by 60%, and reduce total source energy use by 60%. The examples presented in this study are representative of what can be accomplished using currently available materials, components, and equipment options. However, to achieve these benefits several energy-saving strategies must be done right and must also be done in the right combination. Residential energy programs that provide direct support to production builders and minimize the risks associated with changing current construction practices are required to maximize broader benefits to California, including reducing requirements for construction of additional energy generation, transmission, and distribution capacity.

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14. ABSTRACT *(Maximum 200 Words)*

An optimization method based on the evaluation of a broad range of different combinations of specific energy efficiency and renewable-energy options is used to determine the least-cost pathway to the development of new homes with zero peak cooling demand. The optimization approach conducts a sequential search of a large number of possible option combinations and uses the most cost-effective alternatives to generate a least-cost curve to achieve home-performance levels ranging from a Title 24-compliant home to a home that uses zero net source energy on an annual basis. By evaluating peak cooling load reductions on the least-cost curve, it is then possible to determine the most cost-effective combination of energy efficiency and renewable-energy options that both maximize annual energy savings and minimize peak-cooling demand.

15. SUBJECT TERMS

Building America; U.S. Department of Energy; BEopt Building Energy Optimization Software; zero peak cooling demand; energy efficient residential buildings

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