

Analysis of Residential System Strategies Targeting Least-Cost Solutions Leading to Net Zero Energy Homes

Preprint

R. Anderson and C. Christensen
National Renewable Energy Laboratory

S. Horowitz
University of Colorado

*To be presented at the ASHRAE 2006 Annual Meeting
Session: How Low Can You Go? Low-Energy Buildings through
Integrated Design
Quebec City, Canada
June 24–28, 2006*

Conference Paper
NREL/CP-550-38170
April 2006

NREL is operated by Midwest Research Institute • Battelle Contract No. DE-AC36-99-GO10337



NOTICE

The submitted manuscript has been offered by an employee of the Midwest Research Institute (MRI), a contractor of the US Government under Contract No. DE-AC36-99GO10337. Accordingly, the US Government and MRI retain a nonexclusive royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for US Government purposes.

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

Available electronically at <http://www.osti.gov/bridge>

Available for a processing fee to U.S. Department of Energy and its contractors, in paper, from:

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
phone: 865.576.8401
fax: 865.576.5728
email: <mailto:reports@adonis.osti.gov>

Available for sale to the public, in paper, from:

U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
phone: 800.553.6847
fax: 703.605.6900
email: orders@ntis.fedworld.gov
online ordering: <http://www.ntis.gov/ordering.htm>



Analysis of Residential System Strategies Targeting Least-Cost Solutions Leading to Net Zero Energy Homes

Ren Anderson and Craig Christensen
National Renewable Energy Laboratory

Scott Horowitz
University of Colorado

ABSTRACT

The U. S. Department of Energy's Building America residential systems research project uses an analysis-based system research approach to identify research priorities, identify technology gaps and opportunities, establish a consistent basis to track research progress, and identify system solutions that are most likely to succeed as the initial targets for residential system research projects.

This report describes the analysis approach used by the program to determine the most cost-effective pathways to achieve whole-house energy-savings goals. This report also provides an overview of design/technology strategies leading to net zero energy buildings as the basis for analysis of future residential system performance.

BACKGROUND

System Research Objectives

The objectives of the current research project are as follows:

1. Develop integrated energy efficiency and onsite/renewable power solutions that can be successfully used on a production basis to reduce whole-house energy use in new homes by an average of 50% by 2015 and 90% by 2025,
2. Integrate key energy systems innovations from research in new homes into existing homes.

For innovative building energy technologies to be viable candidates over conventional approaches, it must be demonstrated that they can cost-effectively increase overall product value and quality, while significantly reducing energy use and use of raw materials when used on a production basis. The project's team-based systems research approach, including use of systems engineering research techniques, provides opportunities for cost and performance trade-offs that improve whole-building performance and value, while minimizing increases in overall building cost. Systems research is conducted at multiple scales, including individual test houses, pre-production houses, and community-scale developments. Systems research includes analysis of system performance and cost tradeoffs as they relate to whole-building energy performance and cost optimization, including interactions between advanced envelope designs, mechanical and electrical systems, lighting systems, space conditioning systems, hot water systems, appliances, plug loads, energy control systems, renewable energy systems, and onsite power generation systems.

A systems research approach creates process innovations that improve efficiency and flexibility of housing production. Systems research also improves control over component interactions, which further improves home efficiency and performance. In addition, a systems research approach increases value, reduces risks, reduces barriers, and accelerates adoption of new technologies by increasing integration

between the design and construction process, increasing system performance, increasing system cost effectiveness, and increasing system reliability and durability. Test-house-scale, subdivision-scale, and community-scale evaluation of advanced system concepts in partnership with builders, contractors, and state and local governments provide opportunities for early adopters and industry leaders to directly contribute to key results from the research program.

For development of advanced residential buildings, a systems approach (Figure 1) is defined to be any approach that utilizes comprehensive examination and analysis of overall design, delivery, business practices, and construction processes (including financing) and that performs cost and performance tradeoffs between individual building components and construction steps to produce a net improvement in overall building value and performance. A systems approach includes the use of systems engineering and

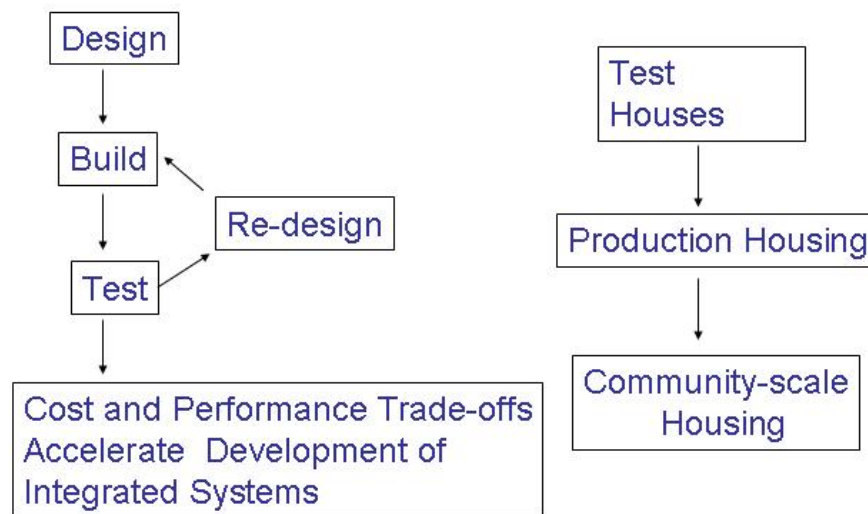


Figure 1. Overview of Building America systems engineering process

operations research techniques. It also requires integrated participation and team building among all parties interested in the building process, including developers, architects, designers, engineers, builders, equipment manufacturers, material suppliers, community planners, mortgage lenders, state and local governments, utilities, and others. Performance results from the evaluation of these systems are presented to a broad residential building science audience via development of technical papers, presentations at major building industry conferences, development of building system performance packages, and development of "train the trainer" curricula based on the key results of the research program.¹

Source and Site Energy Accounting

Energy savings can be defined in terms of site energy (used at the building site) or source energy (sometimes called primary energy). For electricity purchased from a utility, site energy can be converted to source energy as a way of accounting for power plant generation efficiency and electrical transmission and

¹ Building America research results and education materials may be found on <http://www.buildingamerica.gov/>

distribution losses. All energy savings in this paper are based on source energy savings. The source-to-site energy ratio for electricity typically has a value of about 3, depending on the mix of electrical generation types (coal-fired, natural gas combined cycle, nuclear, hydropower, etc.) From the view of all stakeholders in the building process, site and source energy are both important. Source energy has been chosen as the basis for tracking progress toward the energy saving targets for the program and will also be used as the basis of the cost/performance tradeoffs analyzed in this report. Site energy savings are also calculated as part of ongoing research projects and included in project evaluations because of their importance in determining specific utility bill savings.

ANALYZING THE LEAST-COST PATH TO HOMES THAT PRODUCE AS MUCH ENERGY AS THEY USE ON AN ANNUAL BASIS

The research path to future residential energy savings extends from a base case (e.g., a current-practice building, a code-compliant building, or some other reference building) to a Zero Net Energy (ZNE) building with 100% source energy savings². To ensure a well-defined reference for evaluation of energy savings and progress toward multi-year goals, a detailed benchmark building definition has been developed for use by all participants in the project (Hendron 2005). A standard reporting format for research results has also been developed to facilitate comparisons of performance between different research projects (Hendron et al. 2004).

To evaluate the cost required to reach a specific energy target, energy and cost results can be plotted in terms of annual costs (the sum of utility bills and mortgage payments for energy options) versus percent energy savings as shown in Figure 2. The optimal least-cost path can then be determined by connecting the points for building designs that achieve various levels of energy savings at minimal cost (i.e., that establish the lower bound of results from all possible building designs). Alternatively, net present value or other economic figures of merit could be chosen. Inclusion of even a modest number of possible options for major system choices can lead to a very large number of possible building designs. One of the key challenges in developing a practical analysis method is to develop an approach that quickly focuses on the combinations that are nearest to the least-cost limit.

Points of particular interest on the least cost path to net zero energy homes are shown in Figure 2 and can be described as follows: from the Research Benchmark at point 1, energy use is reduced by employing building efficiency options (e.g., improvements in space conditioning systems, hot water systems, lighting systems, thermal distribution systems, etc.) A minimum annual cost optimum occurs at point 2. Additional building efficiency options are employed until the marginal cost of saving energy for these options equals the cost of producing onsite power at point 3. In this study, residential PV systems are used as the system option for onsite power. As research on distributed energy systems continues, it is anticipated that other onsite power technologies will also become available for residential-scale projects. From point 3 on, the building design does not change and energy savings are solely a result of adding additional onsite power capacity, until ZNE is achieved at point 4.

BUILDING ENERGY OPTIMIZATION

Building energy simulations are often used for trial-and-error evaluation of “what-if” options in building design (i.e., a limited search for an optimal solution). In some cases, a more extensive set of options is evaluated and a more methodical approach is used. For example, in a successful California project, energy efficiency measures were evaluated using DOE2 simulations in a sequential analysis method that explicitly accounted for interactions (Davis Energy Group, 1993).

Several computer programs to automate building energy optimization have been recently developed. For example, EnergyGauge-Pro uses successive, incremental optimization (similar to the approach used in the California project referenced above) with calculations based on the “energy code multiplier method” for Florida (Florida Solar Energy Center 2005). GenOpt is a generic optimization program for use with various building energy simulation programs and user-selectable optimization methods (Wetter 2004).

² Energy savings include credit for energy from an onsite power system that is delivered to the grid minus energy used by the onsite power system.

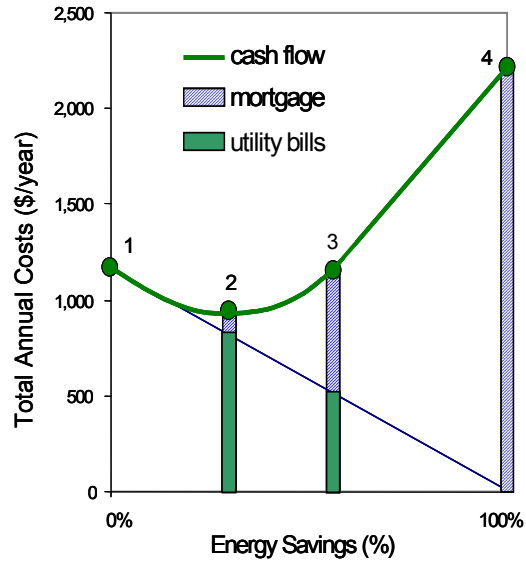


Figure 2. Conceptual plot of the least-cost path to a ZNE home

CONSTRAINED VERSUS GLOBAL OPTIMIZATION

From a purely economic point of view, building energy optimization involves finding the global optimum (the minimum annual cost point 2 in Figure 2) that balances investments in efficiency versus utility bill savings. Given a particular energy savings target, economic optimization can be used to determine the optimal design (lowest cost) to achieve the energy savings goal. This sort of constrained optimization can also apply for other target levels of energy savings between the base case and ZNE and is the basis for establishing the optimal path to zero net energy.

Discrete Versus Continuous Variables

In theory, optimal values can be found for continuous building parameters. In the practice of designing real buildings, however, the process often involves choosing among discrete options in various categories. For example, options in the wall construction category may include 2x4 R11, 2x4 R13, 2x6 R19, 2x6 R19 with 1-in. foam, 2x6 R19 with 2-in. foam, etc.

If discrete option characteristics for a particular category fall along a smooth curve, a continuous function can be used in an optimization methodology along with other discrete and continuous categories. After optimization, the discrete options closest to the optimal values can be selected. However, the resulting combination of options may not necessarily be truly optimal, because when the option nearest (but not equal) to the optimal value in one category is selected, the optimal values for other categories may change.

Even if energy use as a function of a particular building parameter is well behaved, the introduction of costs (e.g., for particular wall construction options) may introduce significant irregularities. In fact, given the discrete products available in many categories (wall construction, glass type, air conditioners, furnaces, etc.), a smooth, continuous energy/cost function occurs in relatively few cases (e.g., loose-fill ceiling insulation). In general, if discrete options are to be considered, they should be dealt with as such.

Near-Optimal Solutions

It is advantageous for the optimization methodology to present multiple solutions (optimal and near-optimal). Near-optimal solutions achieve a particular level of energy savings with total costs close to the optimal solution total cost. Given uncertainty in cost assumptions and energy use predictions, near-optimal points may be as good as optimal points. For various non-energy/cost reasons, the alternative construction

options in near-optimal solutions may be of interest to building designers to facilitate substitutions that meet target market needs without compromising overall system energy performance.

Evaluation of Other Market Drivers in Addition to Energy Cost

The least-cost options identified by the analysis method shown in Figure 2 represent a zero constraint starting point for system studies by project research teams in partnership with the residential construction industry. The proposed analysis method does not currently include models to evaluate the impacts of non-energy market drivers such as durability, reliability, ease of installation, availability of local supply, service, and support centers, or warranty and call-back costs. The initial analysis results presented in this paper are therefore limited to determining the minimum requirement, based on marginal cost and energy performance, for a given design/technology combination to be considered as viable system solution on the least-cost curve. On average, it currently takes about 3 years to evaluate the expected performance benefits of new system concepts, integrate systems into test homes, and evaluate final cost and performance benefits when implemented on a production basis.

IMPLEMENTATION OF A NEW SEQUENTIAL SEARCH TECHNIQUE

The BEopt Analysis Method

In previous papers (Christensen et al. 2003a, 2003b), we described methods to determine the least-cost path to ZNE homes based on the marginal costs of energy efficiency and renewable energy options. We developed methods to determine the path to ZNE by curve fitting a few key points found by optimization using the costs of utility energy and PV energy.

The BEopt analysis method uses an efficient sequential search technique to find optimal and near optimal combinations of discrete energy efficiency options (Christensen et al. 2004). 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 nearly equivalent solutions based on builder or contractor preferences.

Overview of Sequential Search Technique

The sequential search method used by the analysis method involves searching all categories (wall type, ceiling type, window glass type, HVAC type, etc.) for the most cost-effective option 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 option 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.

SAMPLE LEAST-COST SYSTEM OPTIMIZATION RESULTS

Figure 3 shows sample optimization results for points that provide the least overall system costs as a function of source energy savings. The symbols indicate optimal building designs along the least-cost curve (at various levels of energy savings) found by the sequential search technique.

Starting from the base case, total annual costs decrease, while energy savings increase. The initial rate of decrease in annual costs (i.e., the slope of the curve) is remarkably linear. No-cost options (such as window redistributions) lead to pure utility cost savings, which proceed along downward-sloping lines from the base case annual costs (y-axis intercepts) to the lower right corner of the graph (zero utility bill cost, not including hook up charges and fees, at 100% energy savings).

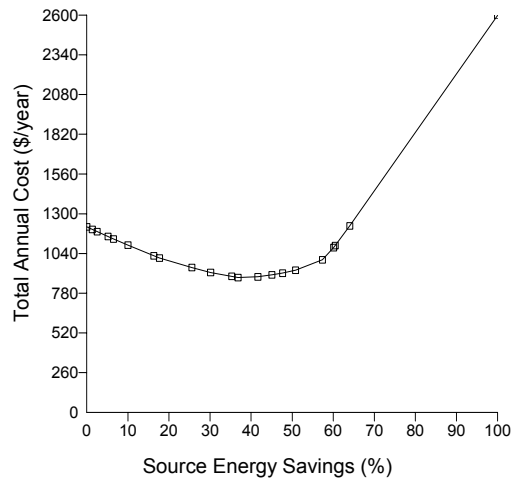


Figure 3. Sample system optimization results showing least-cost system curve

The final straight-line part of the curve corresponds to the incremental cost of using residential PV to offset the remaining energy provided by gas and electric utilities. The slope is proportional to the per Watt cost of PV and inversely proportional to the solar radiation.

A close-up view of all of the points considered by the sequential search in Figure 3 is shown in Figure 4. Each symbol represents a particular simulation in the optimization search with different search iterations indicated by different colors. The analysis method allows the user to step through the results one iteration at a time to see how the optimization progresses. The user can also zoom in, select individual points, display associated building characteristics, and evaluate alternative building designs.

It is important to emphasize that the points on the least-cost curve represent the potential performance that can be achieved by homes that are fully optimized with respect to energy cost performance. The least-cost curve cannot be used as a predictor of actual costs for homes that lie off the least-cost curve.

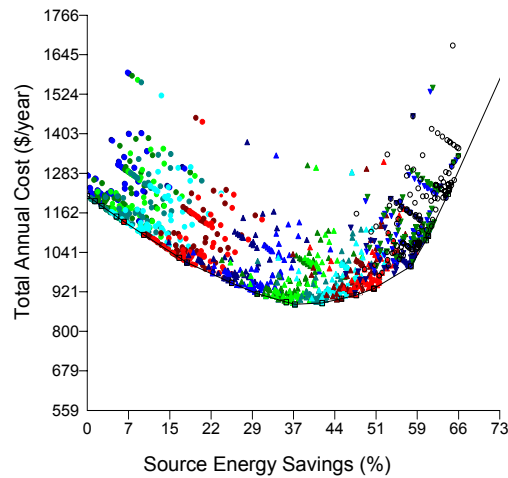


Figure 4. Close-up of sample optimization results showing all points in the neighborhood of the least-cost curve

OVERVIEW OF INPUTS FOR THIS STUDY

The analysis method used in this paper can include any system option or component whose performance can be defined in the context of TRNSYS or DOE2 energy-simulation programs and for which first costs, installation costs, O&M costs, and replacement costs can be specified over a 30-year life. As in any analysis, the results are subject to the assumptions used during the study. For the purposes of evaluating cost performance tradeoffs for near-term project energy performance targets, costs and performance for a range of currently available building materials and components were used in this study.

Building Characteristics Considered in This Study

A simple two-story 1,800-ft² residential building with an attached two-car garage was used for this study with the front of the building facing west. The building is modeled with climate appropriate foundations (e.g., an unconditioned basement in cold climates like Chicago, slab on grade in warm climates like Phoenix). The building has 2-ft eaves. Window area is assumed to be 18% of floor area and is equally distributed between outside walls. Adjacent buildings 10 ft to the north and south provide shading of sidewalls. The study was limited to a worst case (west) orientation. The impacts of other orientations will be considered in future studies. The energy options considered in the study include space conditioning systems (up to SEER 14 in the current study), envelope systems, hot water systems, lighting systems, major appliances, and residential PV. No options that contribute to 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% discount rate. No maintenance costs were included in the study. The specific descriptions of the design options considered in this study cannot be included within the space limitation for this paper and are included in the appendix of Anderson et al. 2004.

Occupancy/Operational Assumptions

Occupancy and operational assumptions are as defined in the 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

Results are calculated relative to a base case building for each climate. Base case buildings are defined in the Research Benchmark, including wall, ceiling, and foundation insulation levels and framing factors, window areas, U-values and solar heat gain factors, interior shading, overhangs, air infiltration rates, duct characteristics, and heating, cooling, and domestic hot water system efficiencies (Hendron 2005).

Cost Assumptions

Each option has an assumed first cost and lifetime. Costs are retail and include national average estimated costs for hardware, installation labor, overhead, and profit. Some are input as unit costs that are then multiplied by a category constant (e.g., ceiling insulation costs are input per square foot and automatically multiplied by ceiling area). Some inputs are energy-option specific (e.g., cost of solar water heating systems). Inputs can also be based on total costs (e.g., cost of wall constructions with different insulation values), because the analysis method will calculate the differences between option costs.

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 mortgage interest rate is 5% above the rate of inflation. 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

O&M costs³. This cost is assumed to be independent of PV system size. Additional costs associated with mounting large PV arrays were not considered. Natural gas is assumed to cost \$1/Therm in all locations. Because of the wide variation in electric cost, local electric costs were used for each city (Table 1).

Table 1. Local Electric Costs Used in Study

City	Electric Cost (\$/kWh)
Atlanta	0.0554
Chicago	0.08275
Houston	0.117
Phoenix	0.081
San Francisco	0.126

The cost estimates used in this study do not include the initial costs required to re-engineer home designs⁴, state and local financial incentives and rebates, or hidden costs, such as warranty and call-back costs that are not already accounted for as part of the O&M costs for the option. All of these additional cost factors can have a significant impact on builder business decisions related to implementation of new system designs.

OVERVIEW OF REQUIREMENTS FOR ZERO NET ENERGY HOMES IN FIVE CLIMATE ZONES

To provide an overall assessment of differences between climates, system optimizations were run for five cities (Atlanta, Chicago, Houston, Phoenix, and San Francisco). These cities correspond to the mixed-humid, cold, hot-humid, hot dry, and marine climates, targeted by the research program (Figure 5).

Least-Cost Path to Zero Net Energy

Figure 6 shows least-cost system curves for a new single-family home in the five cities considered in the study. The y-axis shows energy-related costs, including both utility bills and mortgage payments for energy options. The x-axis shows percent energy savings relative to the Benchmark house definition. Out of all of the different possible combinations of options considered in the sequential search process, the points shown in Figure 6 are the least-cost solutions for the west facing orientation. For the Benchmark buildings (at $x = 0$), annual costs are highest in Houston and lowest in Atlanta.

³ This price may not be currently available in all markets. The DOE Solar Program reports that current residential system PV costs (without including subsidies and O&M costs) are about \$9/W. The Solar Program goal is to reduce base residential system costs from \$9/W to \$5.25/W by 2007 and \$2.80/W by 2020 [10].

⁴ Re-engineering costs include market surveys to evaluate the potential to recover increases in home costs, costs associated with renegotiating relationships with suppliers and contractors, costs required to advertise new home features, technical support required to pass code review of new and innovative systems, 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.

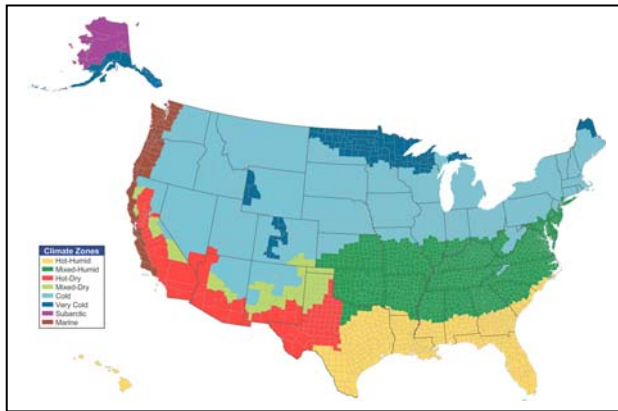


Figure 5. Building America climate zone map

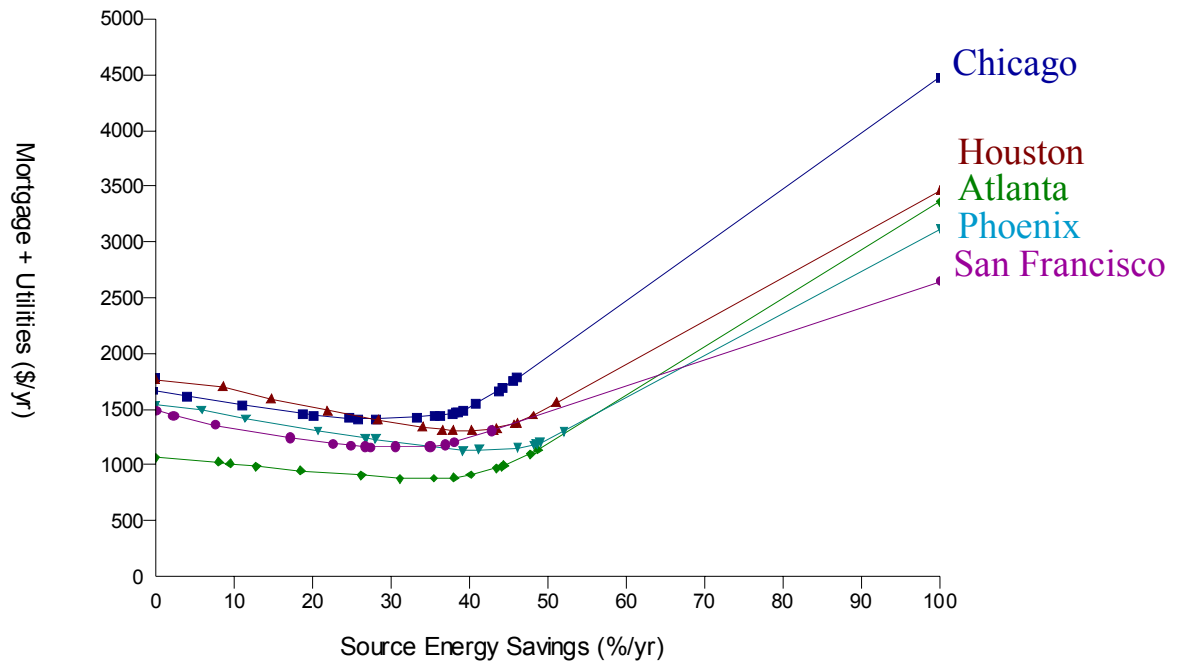


Figure 6. Least-cost curves for five cities

In all cities, total annual costs decrease while energy savings increase starting from the Benchmark. The initial rate of decrease in annual cost versus energy savings (i.e., the slope of the curves) out to the 30% savings point is similar for all five climates. There are several reasons for this similarity. First, the initial slope is set by low cost options with pure utility cost savings, which proceed along downward-sloping lines from the base case annual costs (y-axis intercepts) to the lower right corner of the graph (zero utility bill cost at 100% energy savings). Second, some of the savings are a result of options, such as lighting and appliances, where savings are only weakly climate dependent. Potential cost savings are somewhat less in Atlanta than in other locations because of low energy use and low electric rates.

The minimum cost points occur at approximately 30% for Atlanta, San Francisco, and Chicago and 40% for Houston, and Phoenix. The present value of investments in improved energy efficiency required to operate in the minimum cost area of the curves are summarized in Table 2.

All cost curves are fairly flat out to about 40% and then begin to rise with the exception of Phoenix, where costs don't begin to rise until 50%. The crossover point where investment shifts from energy efficiency to onsite power occurs between 40% (San Francisco) and 50% (Phoenix) depending on climate. The combination of low annual energy use and high electric rates in San Francisco and high annual energy use and low electric rates in Phoenix account for the large difference in the location of the crossover points for these two cities. The final straight-line parts of the curves correspond to the cost of onsite power provided by PV to achieve 100% energy savings.

Recommended Investments in Efficiency for Homes with Integrated Onsite Power Systems

Figure 7 shows the present value of energy efficiency costs at the point where the marginal cost of increasing energy efficiency equals the cost of adding PV. These are the investments in energy efficiency that would be recommended from a least-cost perspective before making investments in PV systems. The recommended investment in energy efficiency upgrades varies by nearly a factor of two from \$8,432 in San Francisco to \$15,166 in Chicago. The PV capacities required to achieve ZNE for the 1,800-ft² home considered in this study and the corresponding energy savings at the crossover point from investment in energy efficiency to investment in onsite power are shown in Table 3.

Table 2. Investment Required to Achieve Minimum Energy Cost

Location	% Whole House Energy Savings at Minimum in Least-Cost Curve	Corresponding Present Value of Investment in New Home Energy Efficiency
Atlanta	32%	\$1749
Chicago	28%	\$3899
Houston	38%	\$2585
Phoenix	39%	\$2585
San Francisco	27%	\$1337

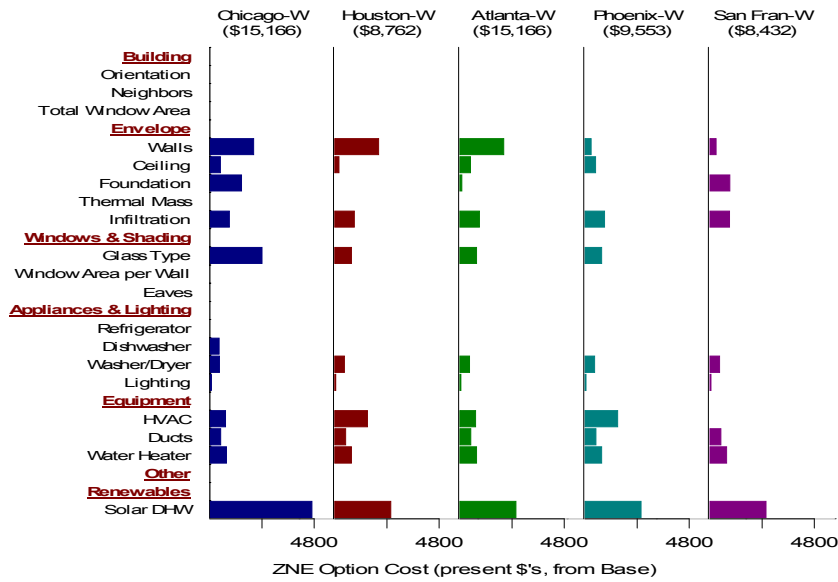


Figure 7. Present value of efficiency options (\$) at the crossover point for investment in onsite power

Table 3. PV Capacities Required to Achieve ZNE, Assuming Maximum Cost-Effective Investment in Energy Efficiency

Location	Crossover Point	PV Capacity Required to Achieve ZNE (kW)
Atlanta	49%	5.6
Chicago	46%	7.6
Houston	51%	6.2
Phoenix	52%	5.4
San Francisco	43%	4.8

Table 4. Cost Multiplier Required to Reach ZNE Relative to Minimum Cost Point

Location	Minimum Cost (\$)	ZNE Cost (\$)	Ratio
Atlanta	1,749	52,351	30
Chicago	3,899	71,874	18
Houston	2,585	56,759	22
Phoenix	2,585	49,679	19
San Francisco	1,337	42,808	32

Based on a review of the location of the crossover points shown in Table 3 and the cost ratios shown in Table 4, additional residential building components will be required to cost effectively meet whole-house residential-building energy-performance goals beyond the year 2010. Additional efficiency improvements in space-conditioning systems, hot-water systems, lighting systems and major appliances are not likely to be sufficient by themselves. Development of cost-effective solutions for miscellaneous electric loads and research leading to significant reductions in the cost of onsite power systems will also be needed. Establishing specifications for the advanced components needed to meet future energy performance goals will be an important research activity for the project over the next several years.

DESIGN/TECHNOLOGY OPTIONS FOR 40% ENERGY SAVINGS IN FIVE CLIMATES

Figures 8-12 provide a summary of the least cost design/technology options required to achieve 40% energy savings in each city. The incremental cost of the last step required to reach 40% is highlighted in with a black arrow on the right-hand side of the figures. The minimum investments required to reach 40% energy savings are summarized in Table 5. The cold climate (Chicago) is the most expensive climate followed by the marine climate (San Francisco). It is more costly to reduce energy use in climates dominated by heating than in climates dominated by cooling. Table 5 also includes the costs required to reach 50% savings without investing in onsite power. In the context of the current study with a base onsite power cost of \$7.50/W, no system solutions were found that could cost effectively reach 50% savings in Chicago or San Francisco without the use of PV.

The specific results shown in Figures 8-12 are subject to the options and assumptions included in the present study and are representative of energy savings and costs that can be achieved after the house re-engineering process has been completed and homes are offered on a production basis. The final system solution chosen by a specific builder will depend on his design objectives, his target market, his assessment of the reliability and constructability of different system options, and the level of technical support for system design changes and quality control that he receives from his suppliers and contractors. Colored points showing other combinations of efficiency options are included in Figures 8-12 to show the additional system solutions that are available in the near neighborhood of the least-cost curve. Options within each category are arranged in terms of increasing cost. The shaded portion of the bars on the right hand side of Figures 8-12 represent the fraction of all possible options within each category that have been considered at each savings level.

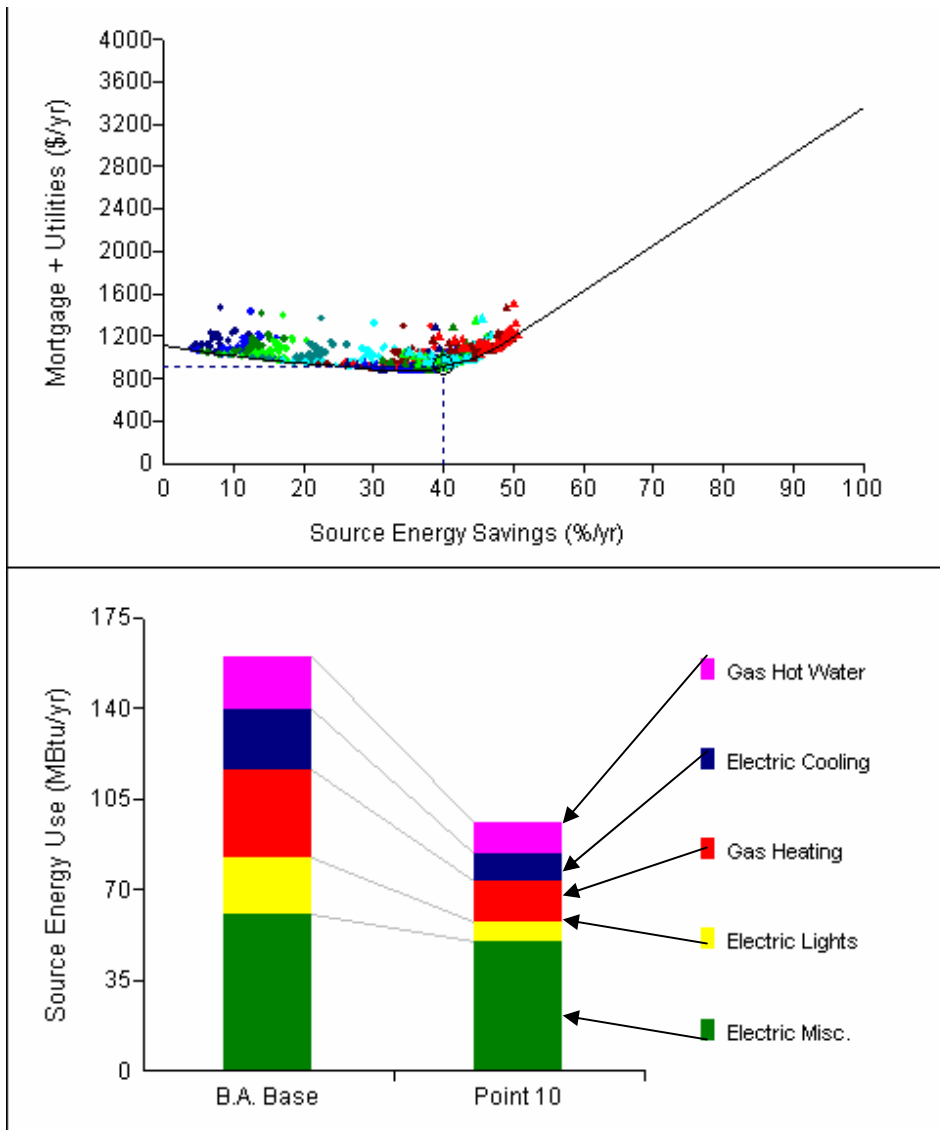
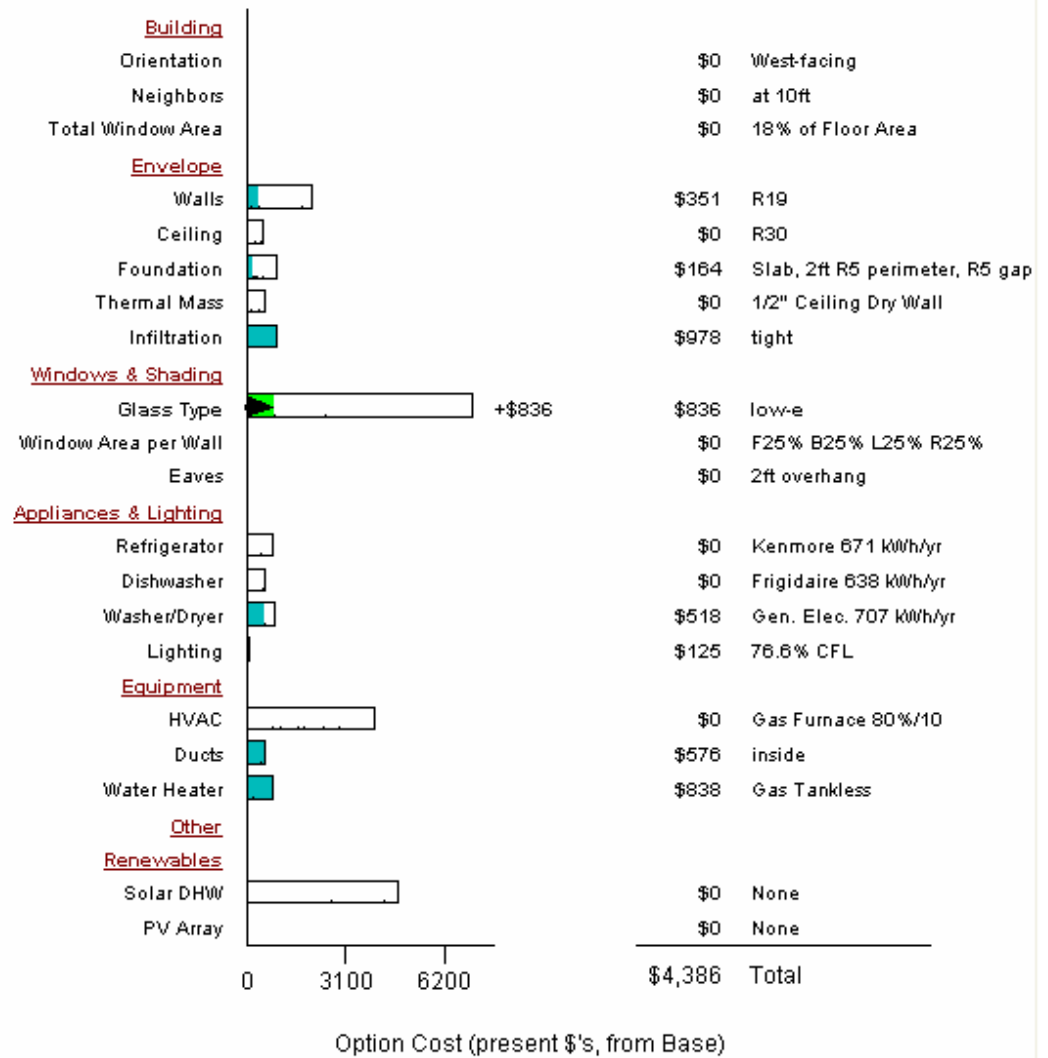


Figure 8. Atlanta 40% savings point



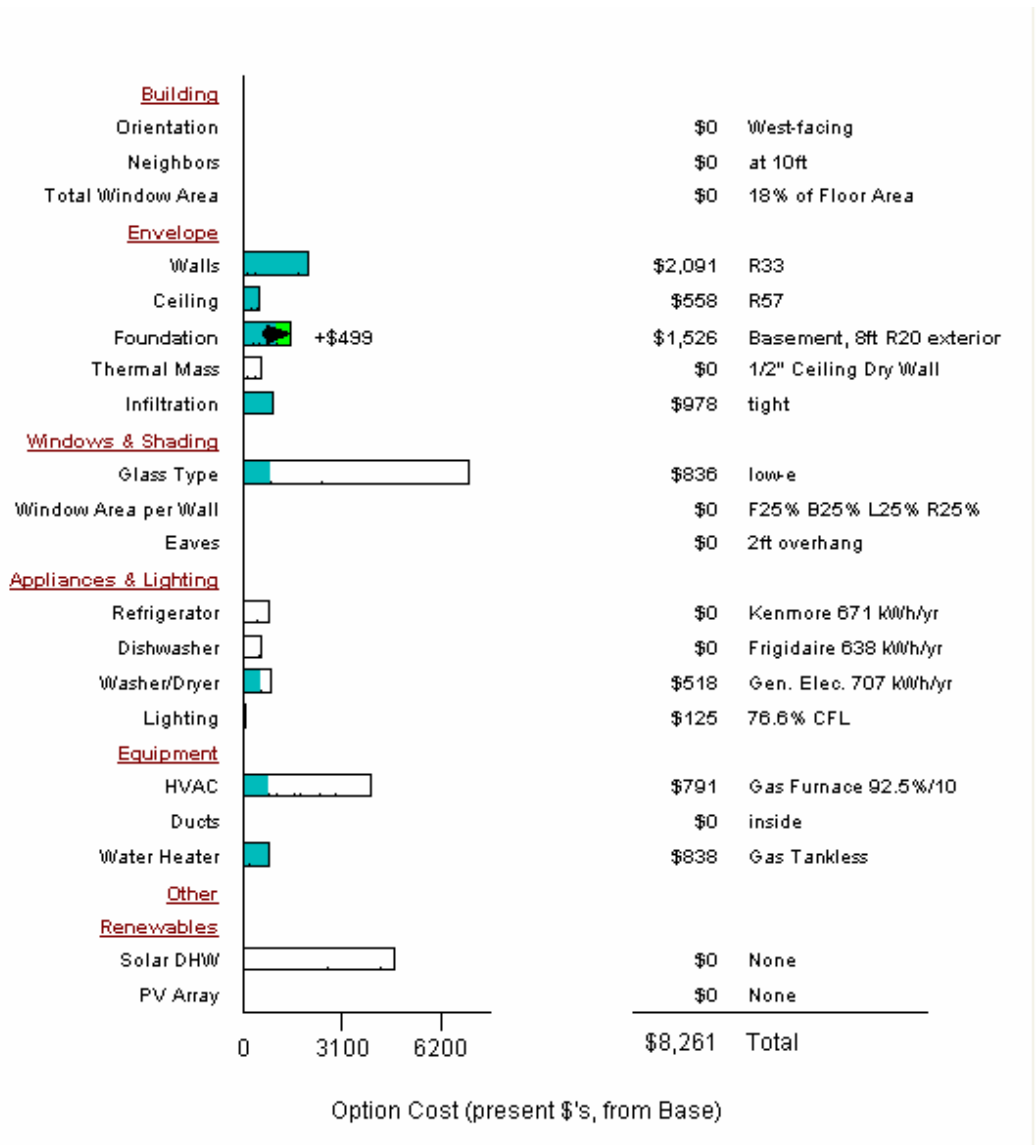
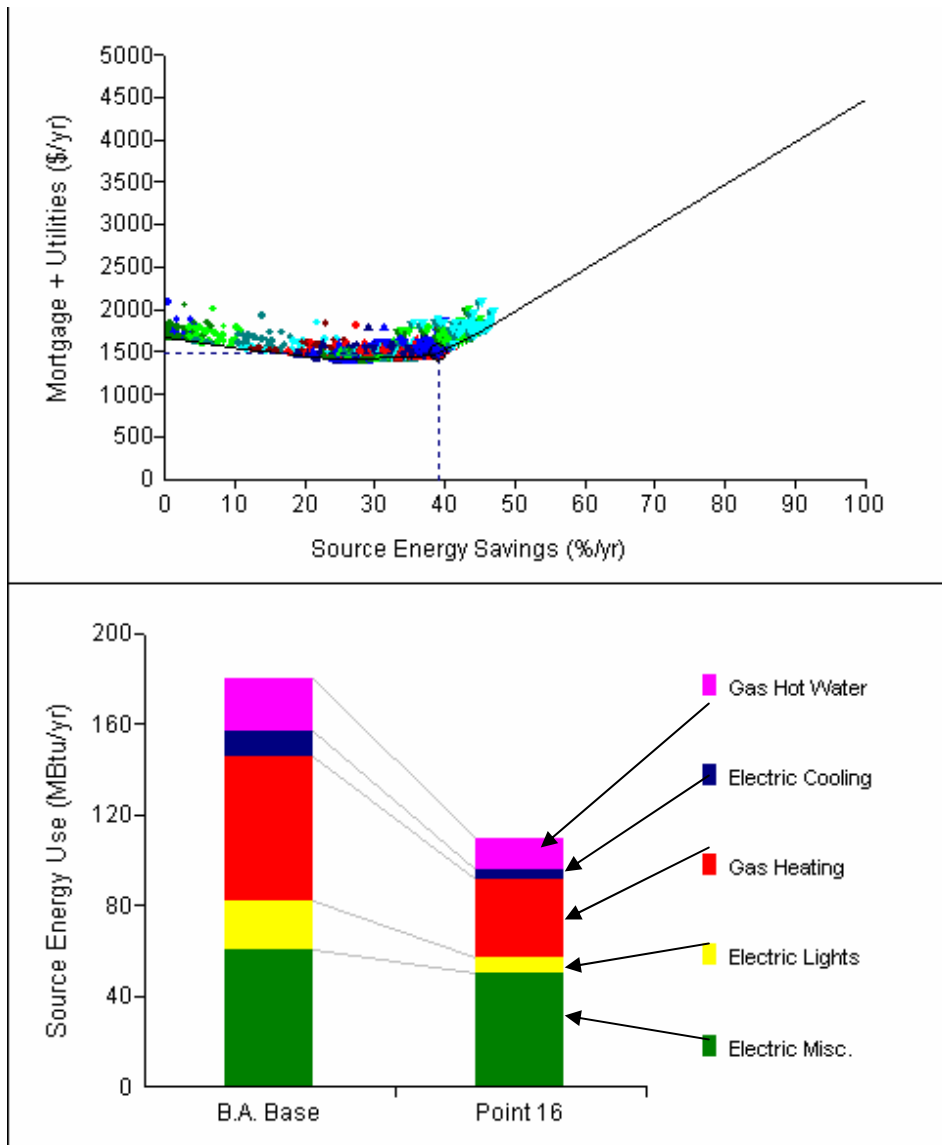


Figure 9. Chicago 40% savings point

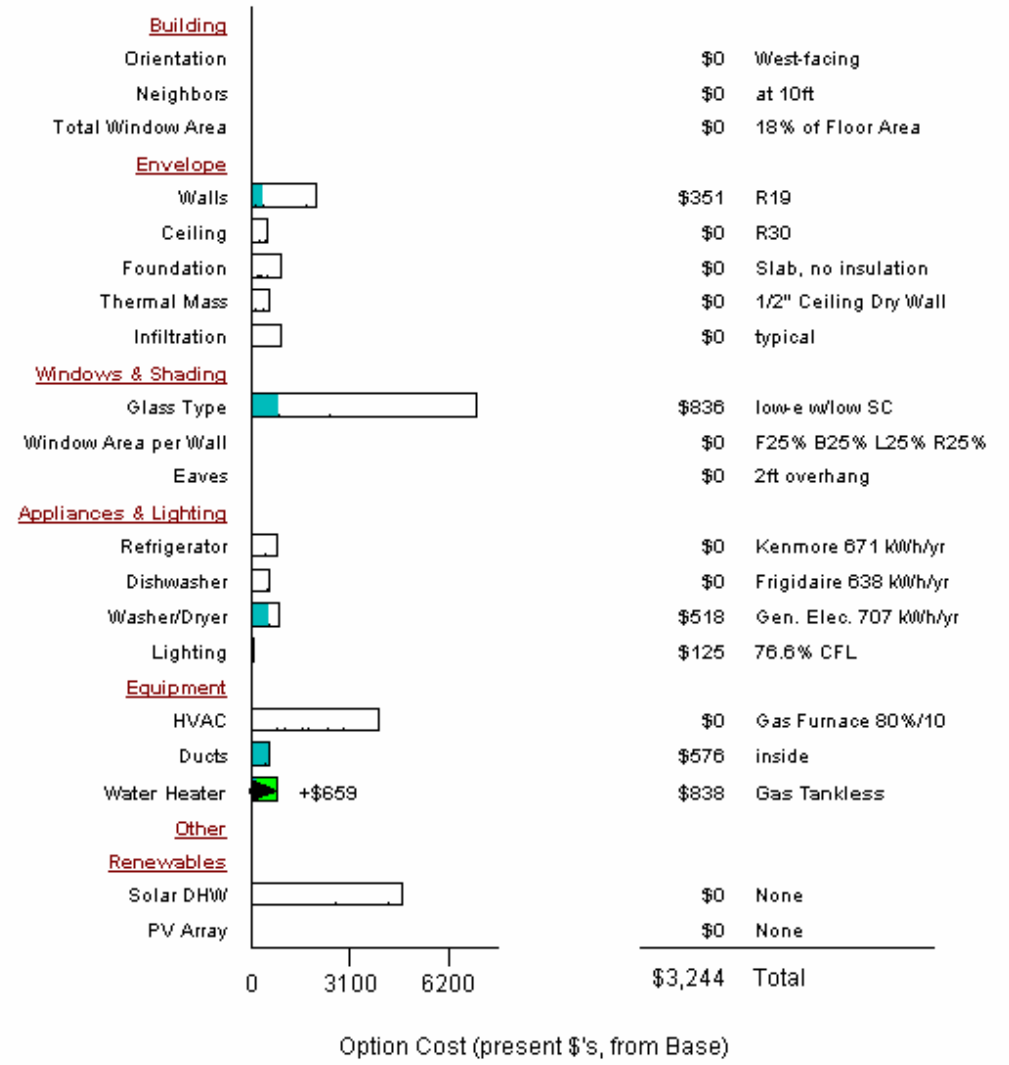
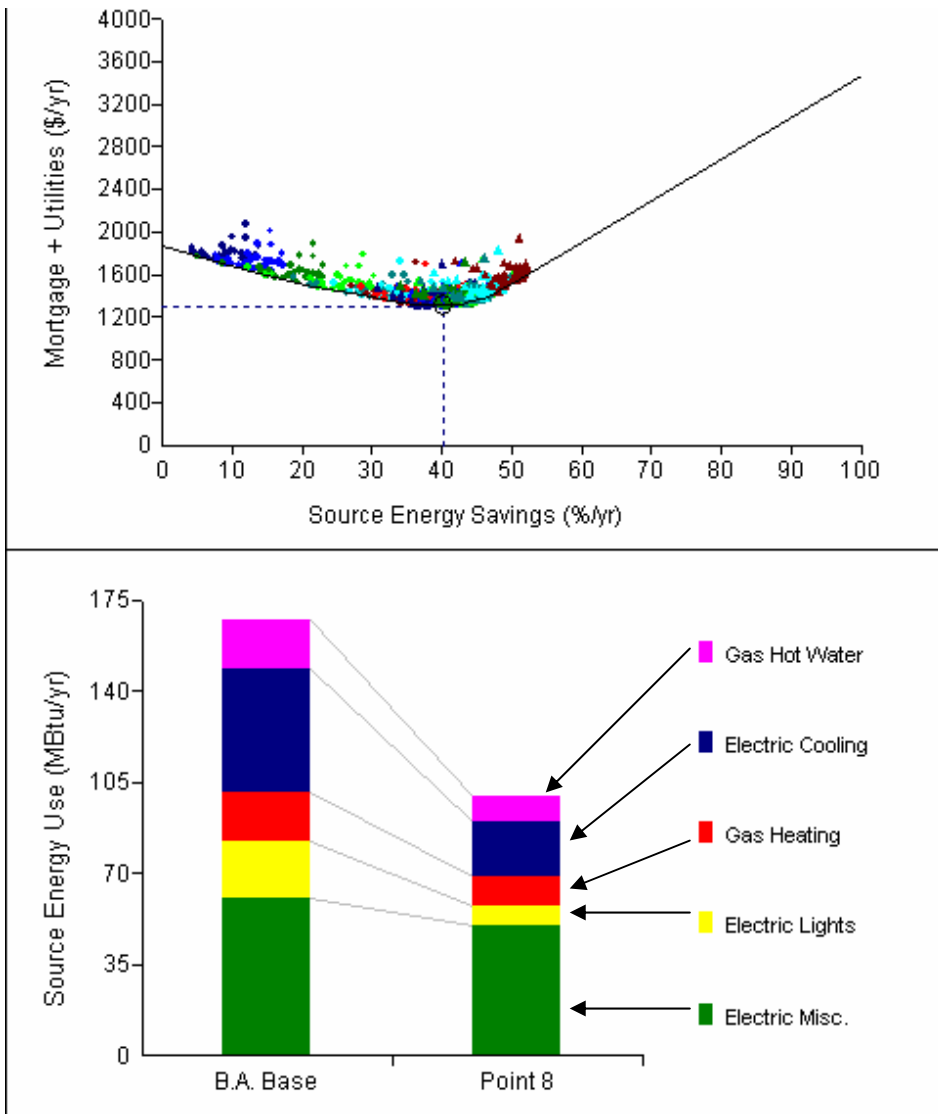


Figure 10. Houston 40% savings point

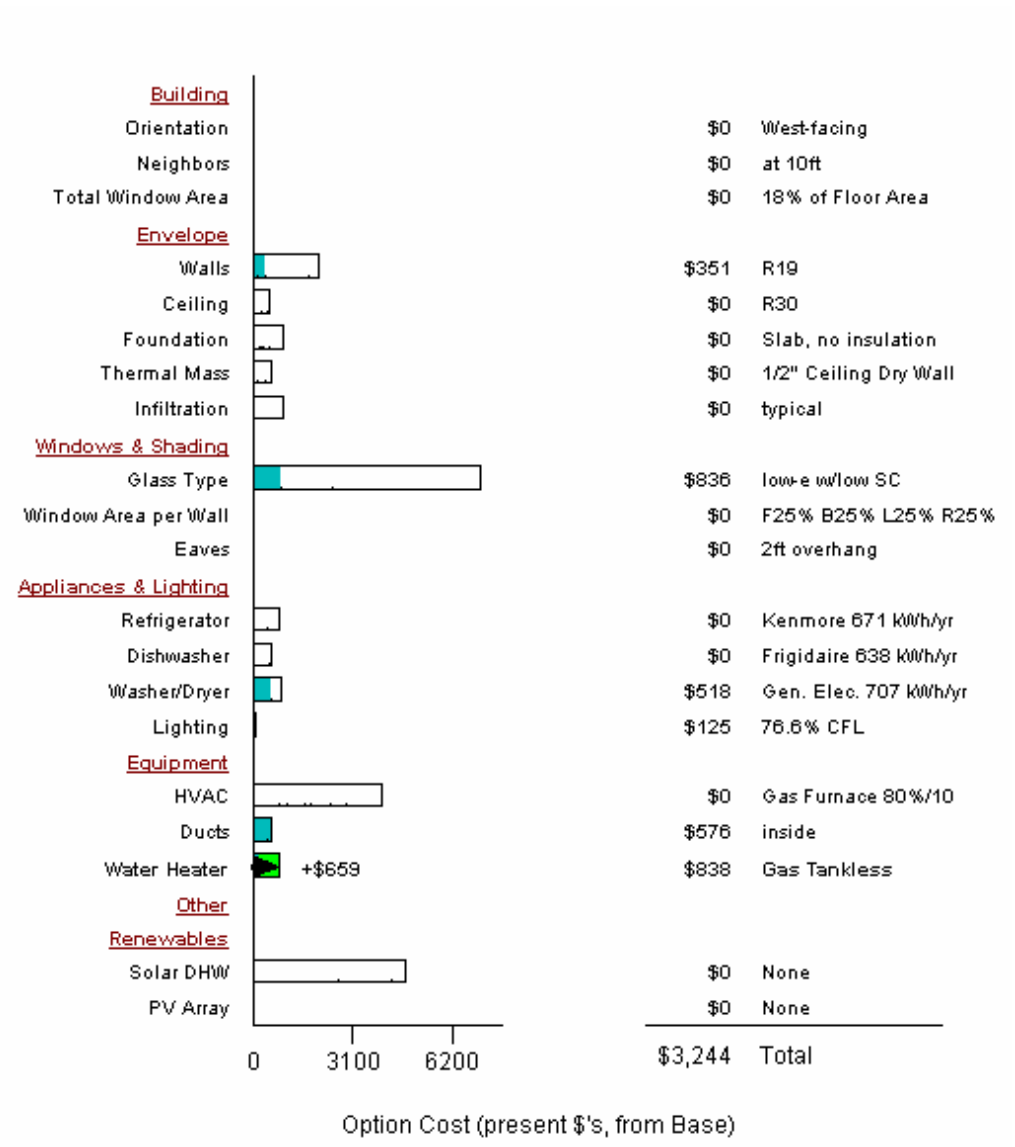
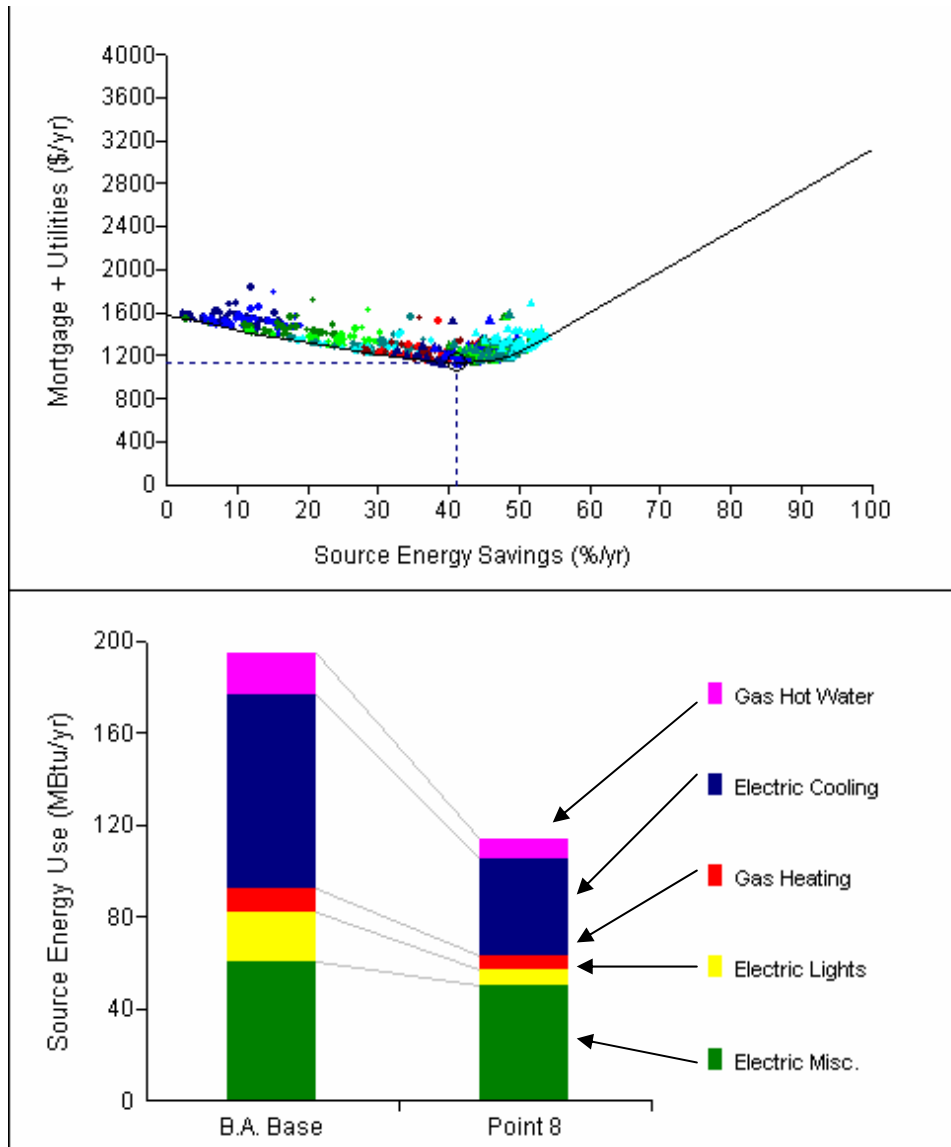


Figure 11. Phoenix 40% savings point

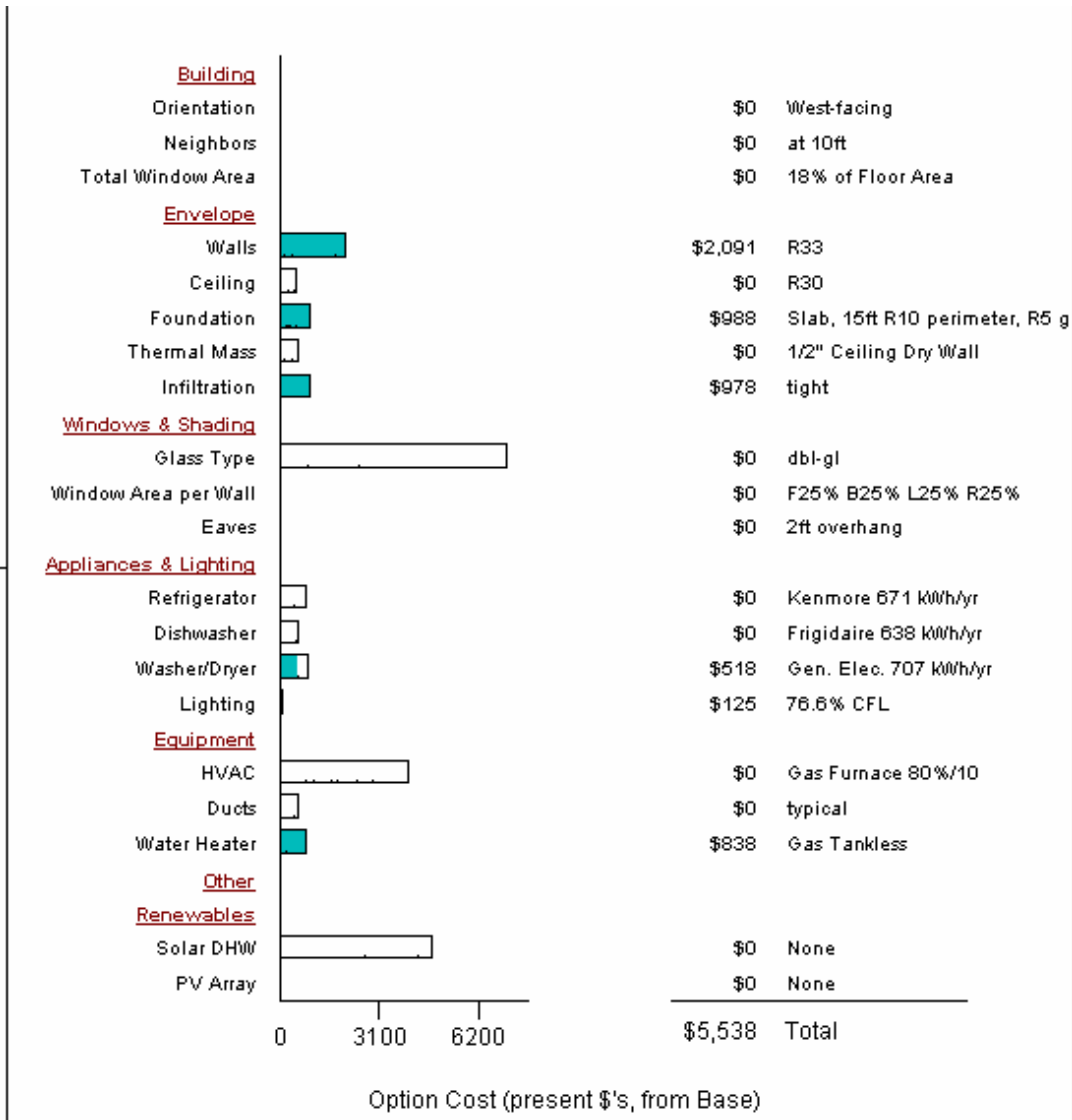
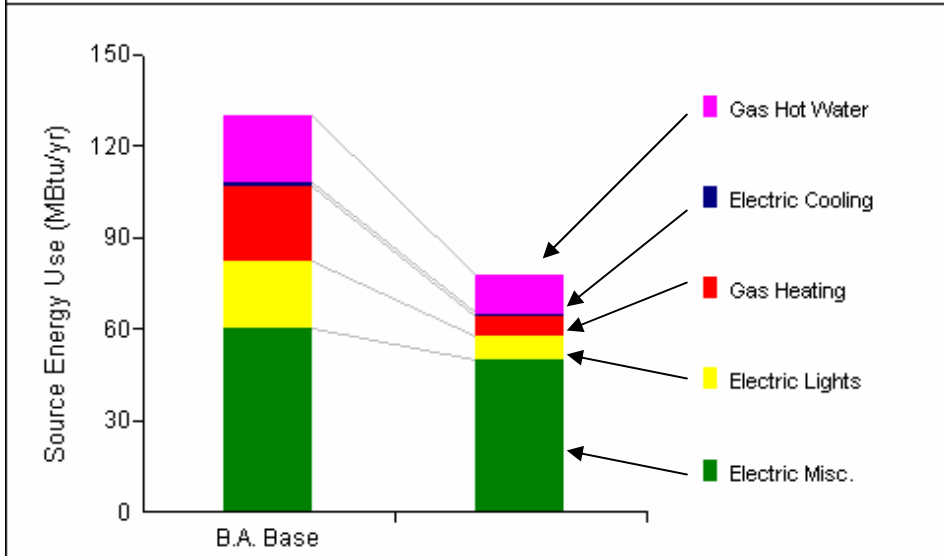
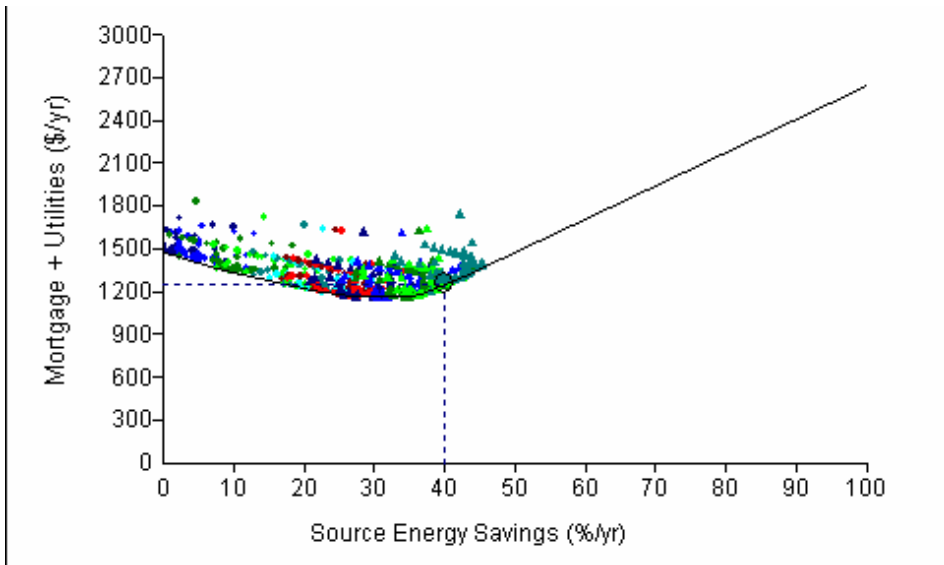


Figure 12. San Francisco 40% savings point

**Table 5. Minimum Investment Required for Reaching
40%-50% Savings without Onsite Power**

Location	Minimum Cost at 40% Point (\$)	Minimum Cost at 50% Point (\$)
Atlanta	4,386	11,452
Chicago	8,261	NA
Houston	3,244	9,896
Phoenix	3,244	7,646
San Francisco	5,538	NA

CONCLUSIONS

The sequential search technique used in the analysis method efficiently identifies the least-cost approach to whole-house energy performance goals based on evaluation of thousands of annual hourly energy simulations involving different combinations of discrete residential system equipment and material options. The sequential search technique utilized in this paper has several advantages. First, it finds intermediate optimal points all along the least-cost curve (i.e., minimum-cost building designs at different target energy savings levels, not just the global optimum or the ZNE optimum). Second, discrete rather than continuous building options are evaluated to reflect realistic construction options. Third, near-optimal designs in the neighborhood of the least-cost curve are identified and retained as alternative solutions depending upon builder and consumer preferences. In addition to simply searching for the sequence of optimal improvements in building design along the least-cost curve, the analysis method also handles special cases with negative interactions: (1) removing previously selected options and (2) re-evaluating previously rejected combinations of options.

The initial analysis presented in this paper has identified the energy related system components and costs required to achieve 40-50% savings levels relative to the Benchmark. Using current component/cost assumptions and assuming no reduction in the use of energy for miscellaneous electric loads other than major appliances, the crossover point on the least-cost curve from energy efficiency to onsite power is projected to occur between the 50% and 60% whole-house energy-savings level.

As with any analysis study, the results of the analysis are subject to the assumptions used during the study. Data from ongoing residential system field studies will be used to validate and update the component cost and performance models used in the present study in collaboration with the project's research teams.

ACKNOWLEDGMENTS

This work was supported by the U.S. Department of Energy, Office of Building Technologies. The support and leadership of Ed Pollock, George James, and Lew Pratsch of the DOE Building America Program, is gratefully acknowledged. We also thank Bob Hendron, Paul Norton, Mark Eastment, Jay Burch, and Ron Judkoff of NREL's Center for Buildings and Thermal Systems, along with Ed Hancock, Paul Reeves and Blaise Stoltenberg for their interest and valuable discussions on the topic of this paper. This work would not have been possible without the continuing research efforts, feedback, and problem-solving contributions of Building America's industry teams who have excelled at finding system solutions on the least-cost curve.

REFERENCES

- Anderson, R., C. Christensen, G. Barker, S. Horowitz, A. Courtney, T. Givler and K. Tupper. 2004. *Analysis of System Strategies Targeting Near-Term Building America Energy-Performance Goals for New Single-Family Homes: FY 2004 Fourth-Quarter Building America Milestone Report*. NREL/TP-550-36920. Golden, CO: National Renewable Energy Laboratory.
- Christensen, C., G. Barker and S. Horowitz. 2004. "A Sequential Search Technique for Identifying Optimal Building Designs on the Path to Zero Net Energy." *Proceedings of the Solar 2004*. Portland, OR: American Solar Energy Society.

- Christensen, C., G. Barker and B. Stoltenberg. 2003a. "An Optimization Methodology for Buildings on the Path to Zero Net Energy." *Proceedings of the Solar 2003*. Austin, TX: American Solar Energy Society.
- Christensen, C., G. Barker and B. Stoltenberg. 2003b. "An Optimization Method for Zero Net Energy Buildings." *Proceedings of the International Solar Energy Conference*. Kohala Coast, HI: American Society of Mechanical Engineers.
- Davis Energy Group. 1993. *ACT2 Stanford Ranch Site, Final Design Report*. Davis, CA: Davis Energy Group.
- Florida Solar Energy Center. 2005. *EnergyGauge Pro*. Cocoa, FL: Florida Solar Energy Center (<http://energygauge.com/FlaRes/features/pro.htm>).
- Hendron, R. 2005. *Building America Research Benchmark Definition, Updated December 29, 2004*. NREL/TP-550-37529. Golden, CO: National Renewable Energy Laboratory.
- Hendron, R., R. Anderson, R. Judkoff, C. Christensen, M. Eastment, P. Norton, P. Reeves and E. Hancock. 2004. *Building America Performance Analysis Procedures: Revision 1*. NREL/TP-550-35567. Golden, CO: National Renewable Energy Laboratory.
- RSMMeans. 1999. *Residential Cost Data- 18th Annual Edition*. Kingston, MA: RSMMeans, Company, Inc.
- Wetter, M. "GenOpt®, "Generic Optimization Program," *Seventh International IBPSA Conference*. Rio de Janeiro, Brazil (http://www.ibpsa.org/bs_01.htm).

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Department of Defense, Executive Services and Communications Directorate (0704-0188). Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ORGANIZATION.

1. REPORT DATE (DD-MM-YYYY) April 2006		2. REPORT TYPE Conference Paper		3. DATES COVERED (From - To)		
4. TITLE AND SUBTITLE Analysis of Residential System Strategies Targeting Least-Cost Solutions Leading to Net Zero Energy Homes: Preprint			5a. CONTRACT NUMBER DE-AC36-99-GO10337			
			5b. GRANT NUMBER			
			5c. PROGRAM ELEMENT NUMBER			
6. AUTHOR(S) R. Anderson, C. Christensen, and S. Horowitz			5d. PROJECT NUMBER NREL/CP-550-38170			
			5e. TASK NUMBER BET6.8004			
			5f. WORK UNIT NUMBER			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401-3393				8. PERFORMING ORGANIZATION REPORT NUMBER NREL/CP-550-38170		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S) NREL		
				11. SPONSORING/MONITORING AGENCY REPORT NUMBER		
12. DISTRIBUTION AVAILABILITY STATEMENT National Technical Information Service U.S. Department of Commerce 5285 Port Royal Road Springfield, VA 22161						
13. SUPPLEMENTARY NOTES						
14. ABSTRACT (Maximum 200 Words) The U. S. Department of Energy's Building America residential systems research project uses an analysis-based system research approach to identify research priorities, identify technology gaps and opportunities, establish a consistent basis to track research progress, and identify system solutions that are most likely to succeed as the initial targets for residential system research projects. This report describes the analysis approach used by the program to determine the most cost-effective pathways to achieve whole-house energy-savings goals. This report also provides an overview of design/technology strategies leading to net zero energy buildings as the basis for analysis of future residential system performance.						
15. SUBJECT TERMS Building America; U.S. Department of Energy; zero energy homes; analysis-based systems research; whole-house energy savings; energy efficient homes						
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UL	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON	
a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified			19b. TELEPHONE NUMBER (Include area code)	