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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


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Abstract

The Building America residential systems research project uses an analysis-based system research approach to accomplish the following tasks:

(1) Identify research priorities

(2) Identify technology gaps and opportunities

(3) Establish a consistent basis to track research progress

(4) Increase the cost effectiveness of research investments by identifying system solutions that are most likely to succeed as the initial targets for residential system research projects.

This report describes the technical approach used by Building America 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.

The initial analysis presented in this paper identifies the energy-related system components and costs required to achieve 40-50% savings levels relative to the Building America 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 investment in energy efficiency to investment in onsite power is projected to occur between the 50% and 60% whole-house energy-savings level.

In addition to evaluating the cost/performance of specific design options, this study demonstrates that *BEopt* can be used to evaluate the impact that new components will have on the shape of the least-cost curve. Components that contribute to solutions that are equivalent to existing solutions will not change the shape of the least-cost curve. New components that move the least-cost curve down and to the right will be required to meet long-term Building America performance goals.

The results from this analysis will be used to identify the cost/performance characteristics required for future building components to successfully target energy-savings levels greater than 50%. 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 Building America research teams.

1. Background

1.1 Building America System Research Objectives

The objectives of the Building America Research Project are to

(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 2010 and 90% by 2020,

(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. Building America's team-based systems research approach, including use of systems engineering and operations 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.

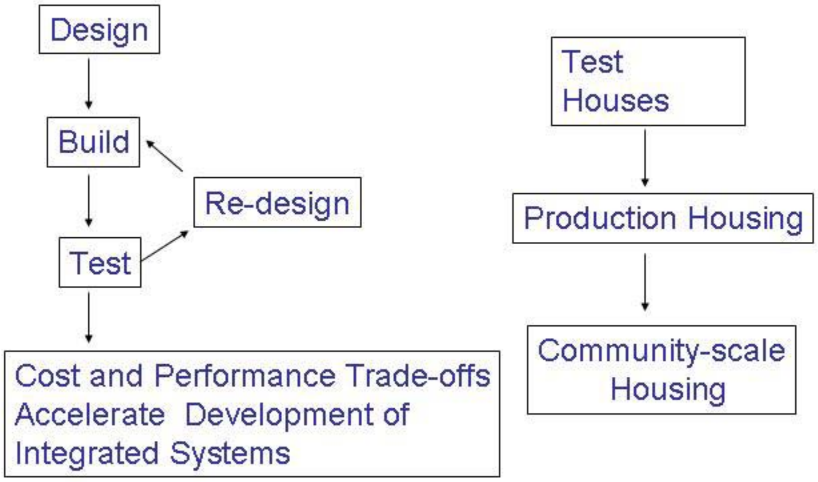


Figure 1. Overview of Building America systems engineering process

For development of advanced residential buildings, a systems approach (Figures 1 and 2) 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 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.

The final products of each research project include performance measurements and cost/performance evaluations in prototype houses, pre-production homes, and community-scale developments, and climate-based system research design/technology packages, including system performance specifications. These measurements, evaluations, and system performance packages, when combined with appropriate policy incentives and included in training curricula and design guidelines, will lead to development of innovative system concepts that can be applied on a production basis by the industry partners and stakeholders involved in the program and their peers.

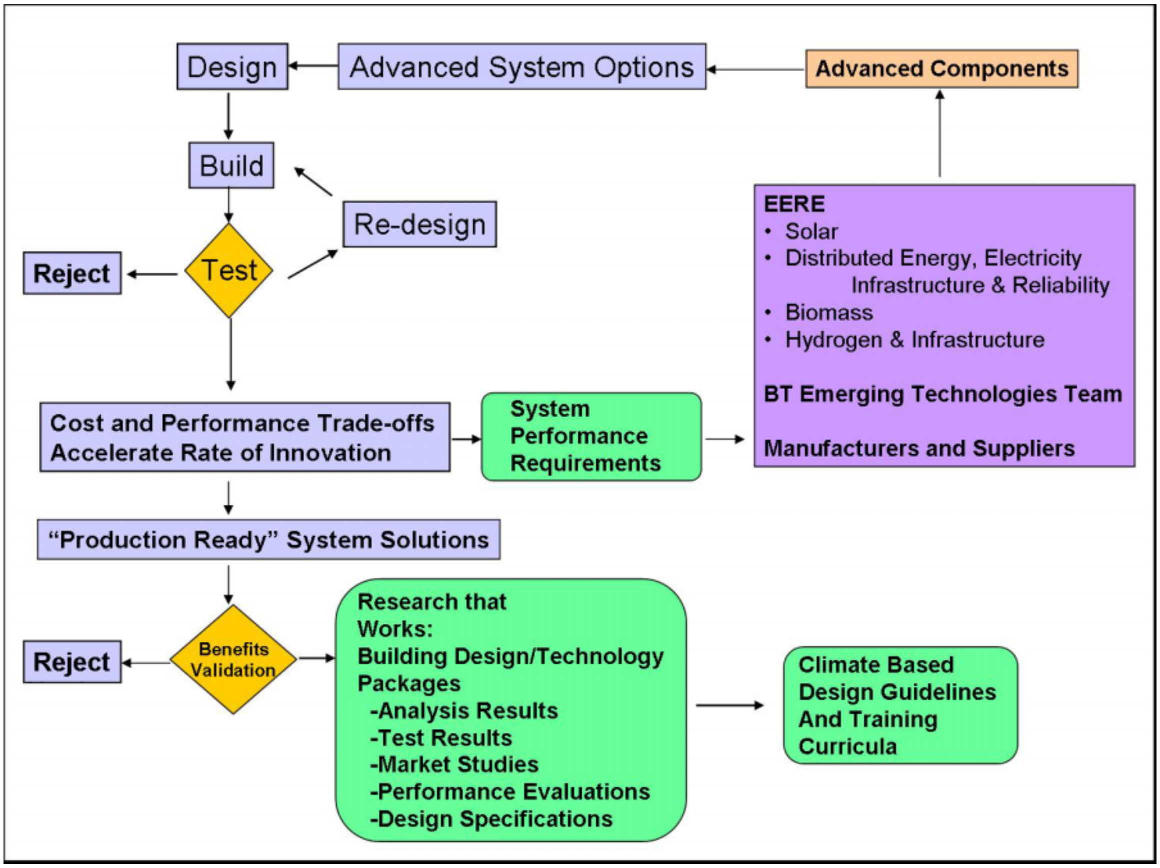


Figure 2. Expanded view of systems engineering process showing key inputs and outputs for the system research process

The range of innovative system concepts considered in Building America research projects include interactions between innovative envelope systems, advanced mechanical and lighting systems, advanced space conditioning systems, efficient water heating systems, renewable energy systems, efficient appliances, energy control systems, and design and construction strategies. 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.

1.2 Building America System Research Activities

Building America's research is organized to facilitate the multi-year research steps required to successfully integrate advanced system concepts into production buildings. The major system research activities that are the focus of Building America projects include the following questions.

Residential Systems Integration R&D

- **Evaluate overall system cost tradeoffs relative to current systems.** What are the system's incremental costs, and how will the system affect overall building costs?
- **Evaluate overall system benefits relative to current systems.** What overall value is delivered by the system to builders? To contractors? To consumers? Examples of system benefits include utility bill savings, contribution to whole-house energy savings goals, increased durability, reduced warranty and callback costs, increased comfort, reduced construction waste, increased labor productivity, increased water efficiency, and increased safety and health.

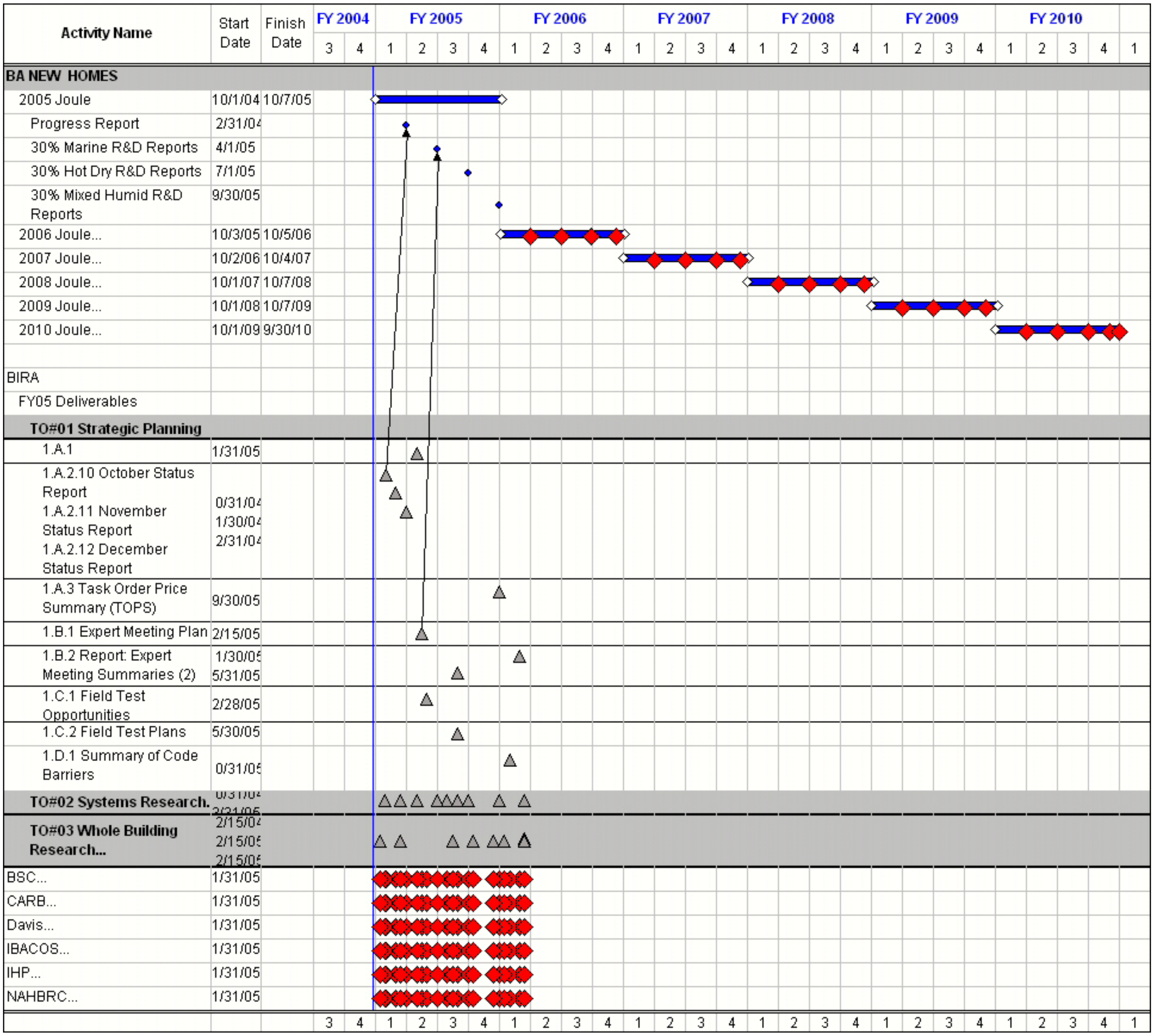
Whole-House Integration R&D

- **Evaluate market impact of new residential energy systems.** What fraction of the residential housing market will be *directly* affected by research results? What are barriers to broad market use? What research can be done to reduce barriers to broad use?
- **Evaluate constructability of new residential energy systems.** What are barriers and risks associated with the use of new systems? Can results be implemented on a production basis? What additional research is required to develop a clear description of whole-house system performance requirements and key system design details that minimize barriers and risks and maximize benefits?
- **Evaluate community-scale benefits of advanced residential energy systems.** What additional benefits will result when systems are implemented on a community scale?

Research Implementation R&D

- **Determine the building science knowledge and outreach approach that is required to successfully hand-off system research results.** Recipients of the research results are residential construction industry leaders, including builders, material suppliers, designers, equipment manufacturers, contractors, and other key stakeholders in the residential construction process.

The relationship between the research activities of individual Building America participants and annual project performance targets is shown in Figure 3. The residential system cost/performance analysis presented in this report is a critical step toward identifying specific system performance gaps and opportunities to support the planning process for future Building America research projects.



Activity Name	Start Date	Finish Date
BA NEW HOMES		
2005 Joule	10/1/04	10/7/05
Progress Report	2/31/04	
30% Marine R&D Reports	4/1/05	
30% Hot Dry R&D Reports	7/1/05	
30% Mixed Humid R&D Reports	9/30/05	
2006 Joule...	10/3/05	10/5/06
2007 Joule...	10/2/06	10/4/07
2008 Joule...	10/1/07	10/7/08
2009 Joule...	10/1/08	10/7/09
2010 Joule...	10/1/09	9/30/10
BIRA		
FY05 Deliverables		
TO#01 Strategic Planning		
1.A.1	1/31/05	
1.A.2.10 October Status Report 1.A.2.11 November Status Report 1.A.2.12 December Status Report	0/31/04 1/30/04 2/31/04	
1.A.3 Task Order Price Summary (TOPS)	9/30/05	
1.B.1 Expert Meeting Plan	2/15/05	
1.B.2 Report: Expert Meeting Summaries (2)	1/30/05 5/31/05	
1.C.1 Field Test Opportunities	2/28/05	
1.C.2 Field Test Plans	5/30/05	
1.D.1 Summary of Code Barriers	0/31/05	
TO#02 Systems Research.	0/31/04 2/21/05	
TO#03 Whole Building Research...	2/15/04 2/15/05 2/15/05	
BSC...	1/31/05	
CARB...	1/31/05	
Davis...	1/31/05	
IBACOS...	1/31/05	
IHP...	1/31/05	
NAHBRC...	1/31/05	

Figure 3. Linkage between individual research activities and annual performance targets[1]

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[1] FY2005 Building America Gantt Chart, Version 1.0

1.3 Broad Building America System Research Benefits

In addition to the direct savings associated with the energy performance goals that are Building America's primary focus, the systems research approach used by Building America also provides a broad range of additional benefits:

- Accelerated development and implementation of advanced energy systems in new and existing homes, including integration of renewable energy and onsite power systems
- Reduced residential construction site waste, increased use of recycled materials, increased labor productivity, reduced construction cycle time, increased system durability and reliability, reduced risk, and reduced warranty and call-back costs
- Development of innovative systems and strategies that enable the U.S. housing industry to deliver environmentally sensitive, high-quality, safe, and comfortable housing on a community-scale, while maintaining profitability and competitiveness of homebuilders and product suppliers
- Increased housing value, durability, and affordability for U. S. homeowners
- Reduced residential peak loads.

These additional benefits, which result from use of a whole-system approach, are critical for commercialization of Building America research results by industry partners. They provide the additional value, in addition to energy savings, required to drive broad market adoption of energy-efficient residential building technologies.

1.4 Multi-year Building America Performance Targets

Within current resource constraints, Building America research projects focus on development of cost-effective, production-ready systems that will reduce energy use by an average of 50% in new single-family homes by the year 2010 and an average of 90% by the year 2020. Limited research on systems for affordable homes, existing homes, and multi-family homes is also included in Building America projects to the extent that research projects in these other market sectors can be successfully integrated as part of ongoing research efforts that focus on new single-family homes. The estimated relative contributions from energy efficiency and onsite power systems leading to 2010 energy performance targets are shown in Figure 4 and summarized in Table 1. Annual performance targets as a function of climate are shown in Table 2.

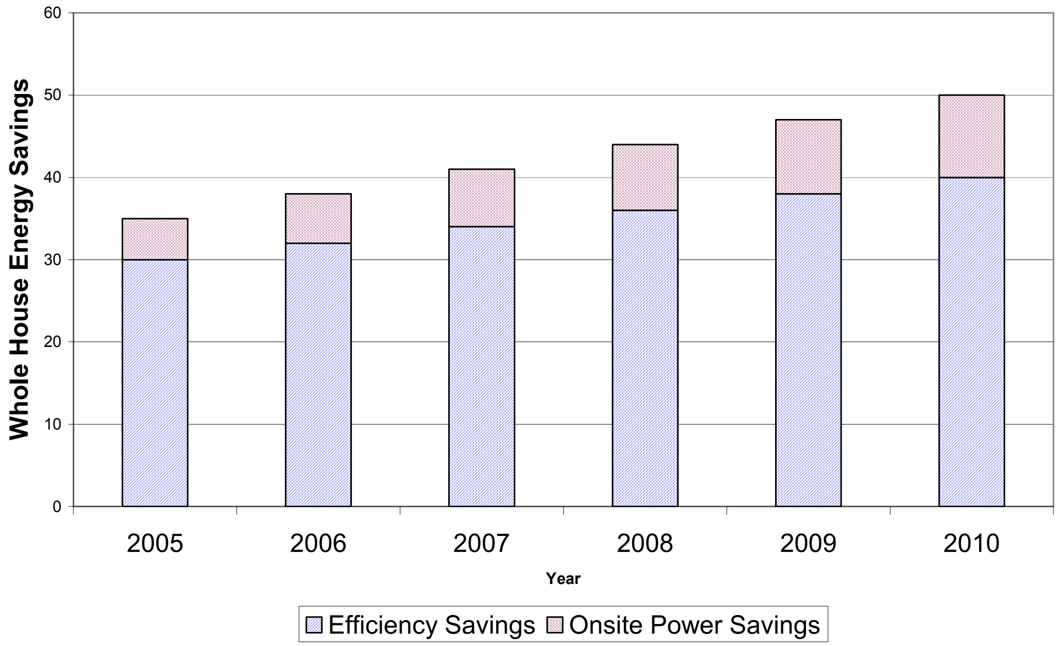

Figure 4. Near-term targets for new single-family homes showing estimated contributions from energy efficiency and onsite power

Table 1. Summary of Building America Near- and Long-Term Performance Targets

New Home Energy Performance Goals (% Whole House Source Energy Savings)				
	2005	**2010**	**2015**	**2020**
Efficiency	30	40-50	50-60	60-70
Onsite/Renewables	0 to 5	5 to 10	10 to 20	20 to 30
Total (mean)	30	50	70	90-100
Existing Home Energy Performance Goals				
Efficiency	TBD	TBD	TBD	TBD
Onsite/Renewables	TBD	TBD	TBD	TBD
Affordable Housing Energy Performance Goals				
Efficiency	TBD	TBD	TBD	TBD

Major Housing Types Currently Targeted by Building America

Affordable housing (Habitat, HUD housing, HUD Code)
Manufactured housing (panelized, modular)
Single-family, detached, site built
Single-family, attached, site built
Multi-family, less than three floors (as part of single-family community projects)
Existing Homes (using systems developed as part of new single-family projects)

Major Climate Zones Currently Targeted by Building America

Marine
Hot Humid
Hot Dry/Mixed Dry
Mixed Humid
Cold

Table 2. Near-Term Residential System Performance Targets by Climate

New Single-Family Homes[2]

	Climate Zone					
Energy Savings[3]	**Marine**	**Hot Humid**	**Hot Dry**	**Mixed Humid**	**Cold**	**Very Cold**[4]
30%	2005	2006	2005	2005	2006	
40%	2006	2007	2006	2007	2008	
50%	2008	2009	2009	2010	2010	

Existing Homes[5]

	Climate Zone					
Energy Savings	**Marine**	**Hot Humid**	**Hot Dry**	**Mixed Humid**	**Cold**	**Very Cold**
30%						
40%						
50%						

New Multi-family Homes[6]

	Climate Zone					
Energy Savings	**Marine**	**Hot Humid**	**Hot Dry**	**Mixed Humid**	**Cold**	**Very Cold**
30%						
40%						
50%						

The climate zone definitions used by Building America are based on groupings of IECC code zones with similar thermal and moisture characteristics (Figure 5). A detailed description of the Building America climate zones, including a listing of Building America climate zone by county, can be found on http://www.buildingamerica.gov/.

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[2] Performance targets are met by research design/technology reports describing production-ready system solutions leading to the indicated level of energy savings and include analysis results, field test results, and case study specifications. At the request funding level, research will focus on new single-family homes in five climate zones.
[3] Energy saving are evaluated relative to the Building America Research Benchmark and include contributions from increased energy efficiency and integrated onsite power systems.
[4] There are insufficient resources at the request level to address very cold or subartic climates.
[5] TBD when system developments from new single-family homes can be applied to existing homes.
[6] TBD when multi-family projects develop as part of community-scale single-family projects.

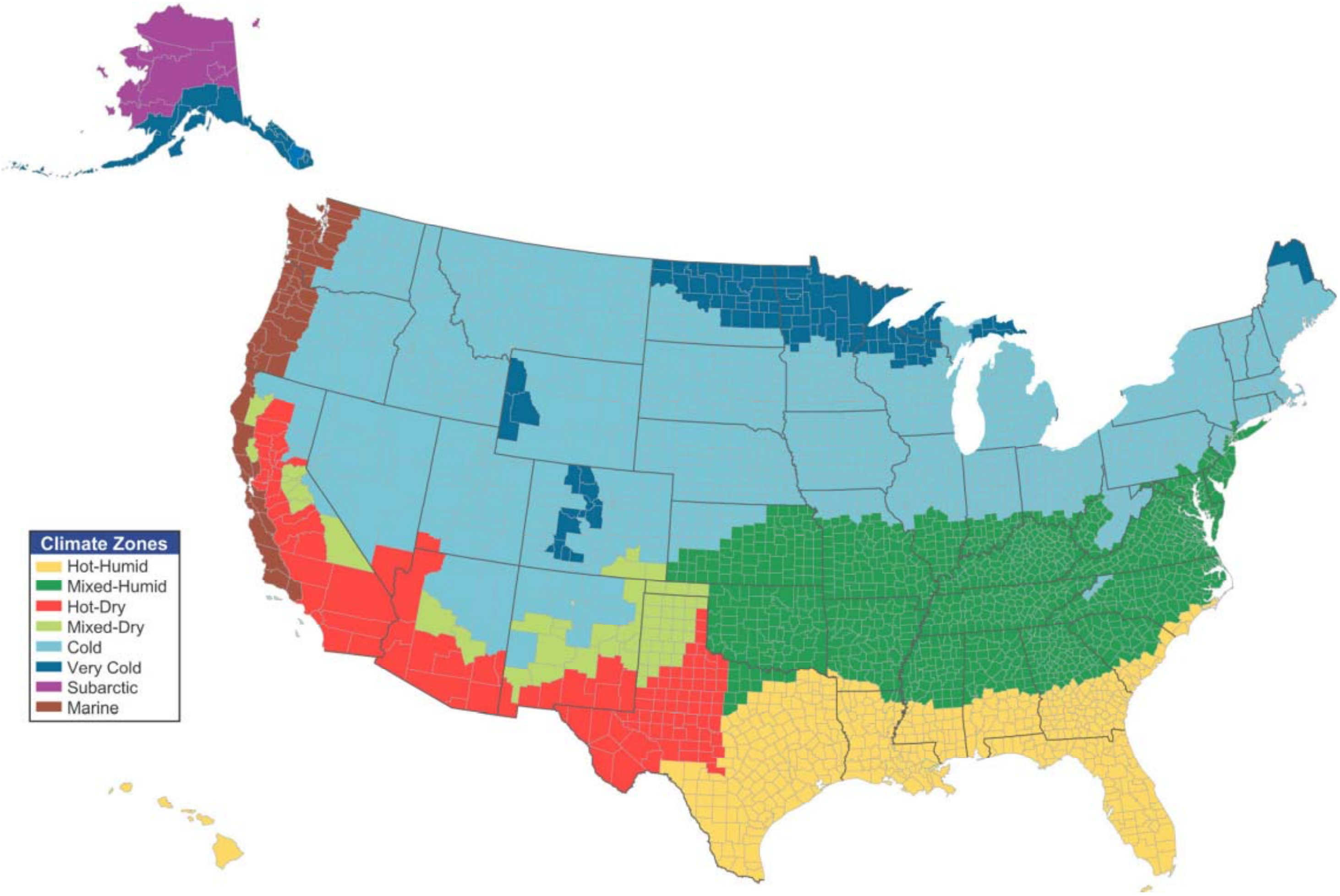

Figure 5. Building America climate zone map

1.5 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 to account for power plant generation efficiency and electrical transmission and distribution losses. 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 in Section 1.4 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.

2. 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% energy savings[7]. 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 Building America research projects [1]. A standard reporting format for research results has also been developed to facilitate comparisons of performance between different research projects [2].

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 6. 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.

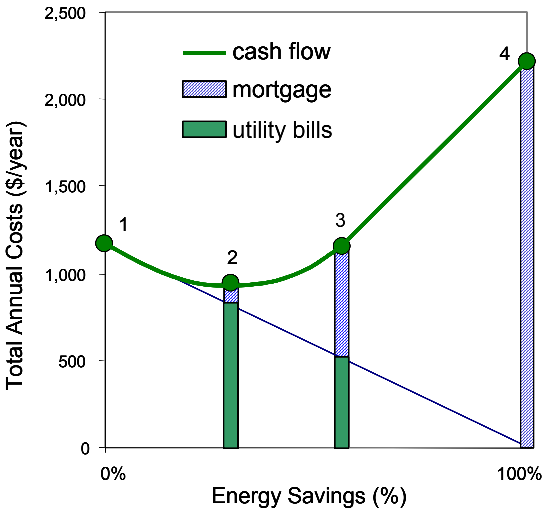

Figure 6. Conceptual plot of the least-cost path to a ZNE home

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[7] 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.

Points of particular interest on the path are shown in Figure 6 and can be described as follows: from the Building America 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 power 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.

3. 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 the Pacific Gas and Electric ACT^2 project, energy efficiency measures were evaluated using DOE2 simulations in a sequential analysis method that explicitly accounted for interactions [3].

With today’s computer power, the bottleneck is no longer simulation run time, but rather the human time to handle input/output. Computerized option analysis has the potential to automate the input/output, evaluate many options, and perform enough simulations to explicitly account for the effects of interactions among combinations of options. However, the number of simulations still needs to be kept reasonable, by using a search technique rather than attempting exhaustive enumeration of all combinations of options. Even with simulations that run in a few seconds, run time for an exhaustive study of all possible combinations is prohibitive for the millions of combinations that can result from options in the ten or more categories needed to accurately describe a residential building.

Several computer programs to automate building energy optimization have been recently developed. For example, EnergyGauge-Pro uses successive, incremental optimization (similar to the ACT^2 approach) with calculations based on the “energy code multiplier method” for Florida [4]. GenOpt is a generic optimization program for use with various building energy simulation programs and user-selectable optimization methods [5].

3.1 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 6) that balances investments in efficiency versus utility bill savings. However, there are sometimes non-economic reasons for targeting particular level of energy 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.

3.2 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.

3.3 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.

3.4 Evaluation of Other Market Drivers in Addition to Energy Cost

The least-cost options identified by *BEopt* (see section 4) represent a zero constraint starting point for system studies by Building America research teams in partnership with the residential construction industry. *BEopt* 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. Initial *BEopt* analysis results 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. Research results from Building America field studies will be used in the future to compare actual incremental cost and performance impacts with those estimated by *BEopt* to ensure that *BEopt* option descriptions accurately reflect overall system costs and benefits.

4. Implementation of BEopt's Sequential Search Technique

4.1 BEopt Software

In previous papers [6, 7], we have described methods to determine the least-cost path to ZNE homes based on the marginal costs of energy efficiency and renewable energy options and 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.

Currently, the *BEopt* program uses a sequential search technique [8]. The choice of this methodology was influenced by several factors. First, intermediate optimal points all along the path are of interest (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 to be evaluated to reflect 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.

BEopt, a program for building energy optimization, calls DOE2 and TRNSYS and then automates the optimization process (Figure 7). *BEopt* scans the specified DOE2 and TRNSYS input files to identify categories and options that are then displayed so the user can select options to be evaluated. Then, an optimization is run and results are shown graphically. *BEopt* can also be used to run parametric simulations based on combinations of the options selected.

The DOE-2 simulation program [9, 10] is used to calculate energy use as a function of building envelope options and heating, ventilation, and air conditioning (HVAC) equipment options. Appliance and lighting option energy savings are calculated based on energy-use-intensity factors and schedules input into DOE-2. TRNSYS [11] is used to calculate water-heating loads and energy savings for solar water heating. TMY2 weather data [12] are used for all simulations.

The TRNSYS simulation program is also used to calculate annual electrical energy production from a grid-tied PV system. The PV array is modeled using the approach developed by Sandia National Laboratories [13] and the database of performance characteristics published on its Web site (http://www.sandia.gov/pv/pvc.htm). Perfect maximum power point tracking is assumed. The inverter efficiency is assumed to follow the shape of a Trace SW series inverter, with a capacity of 1.2 times the rated PV array output at standard rating conditions.

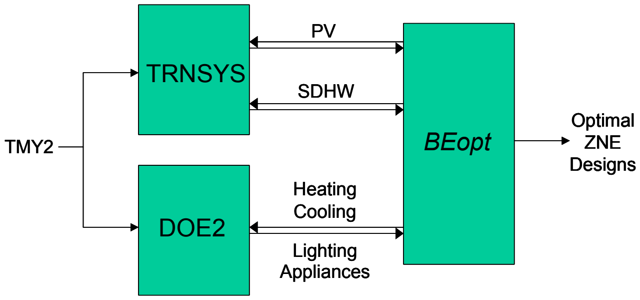

Figure 7. Optimization with multiple simulation programs

4.2 *Sequential Search Technique*

The sequential search method used by *BEopt* 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 (Figure 8). 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.

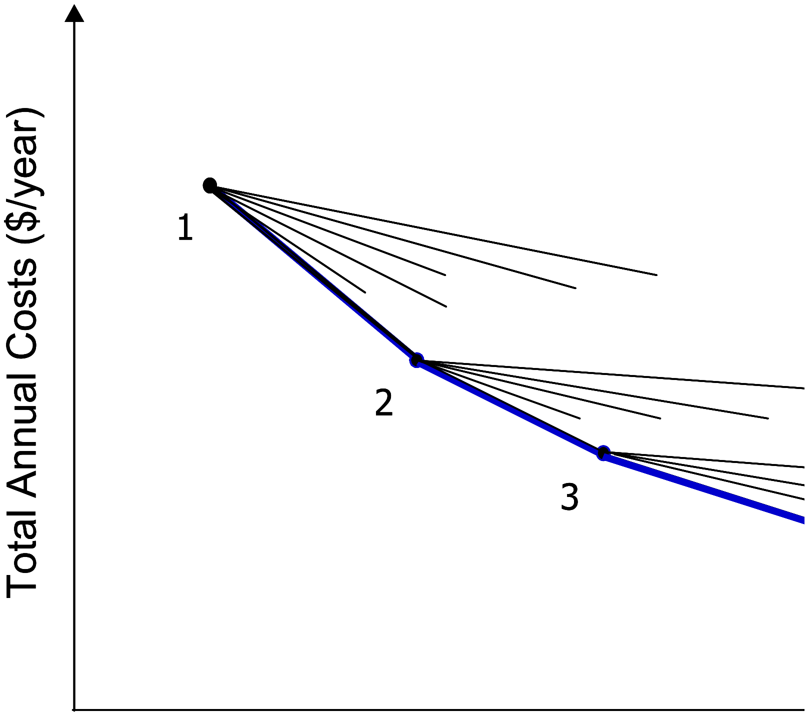

Figure 8. Illustration of sequential search technique

4.3 Special Cases

Figure 8 shows one fewer option being evaluated in each successive iteration. This would be the case if, once an option is included, that option remains in the building design as the building undergoes further improvements. Also, all options are selected in the "forward" direction (i.e., with positive energy savings).

Invest/Divest

The *BEopt* search technique does not assume that once an option is in the building design, it stays in. In addition to evaluating new options, each iteration evaluates the removal of options in the current building design. This can result in negative energy savings and points to the left of the current point. These backward-looking evaluations allow for the possibility that one aspect of the building (say, HVAC efficiency) may initially be improved; then when other aspects (say, envelope insulation levels) are sufficiently improved and loads reduced, it may no longer be cost optimal to have highly efficient HVAC. This phenomenon is illustrated in Figure 9: starting at point 1 (A1, B1), category B is improved to point 2 (A1, B2) and again to point 3 (A1, B3). On the next iteration, an optimal point is found by looking backward to point 3' (A0, B3) where reduced investment in category A is more cost-effective than continuing with high levels of investment in categories A and B. In this case, *BEopt* replaces point 3 with point 3' and proceeds.

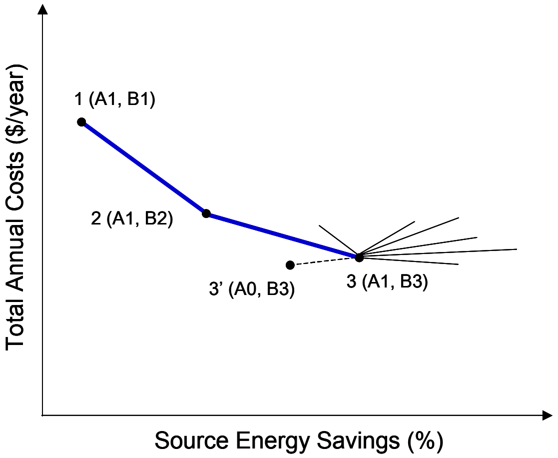

Figure 9. Illustration of an invest/divest special case

Large Steps

BEopt also keeps track of points from previous iterations and checks to see whether they may be better than results of the current iteration. This phenomenon is illustrated in Figure 10: starting at point 1 (A1, B1), a large energy-savings option (in category A) at point 3' (A2, B1) is less cost-effective than a small energy-savings option (in category B) at point 2 (A1, B2). However, when another option (say, option A2 again) is added to achieve the additional energy savings at point 3 (A2, B2), it turns out to be less cost-effective than the original large-savings option at point 3' because of negative interaction between options A2 and B2. In this case, *BEopt* replaces point 3 with point 3' and proceeds.

Positive Interactions

The previous two special cases involved negative interactions between options; a third type of special case involves synergistic interactions. For example, thermal mass may facilitate passive solar heating with extra south-facing window area. This phenomenon is illustrated in Figure 11: starting at point 1 (A1, B1), point (A1, B2) is rejected, while point 2 (A2, B1) is selected. But then, with option A2 in place, the performance of option B2 is so improved that the superior performance of point 3 (A2, B2) eliminates point 2.

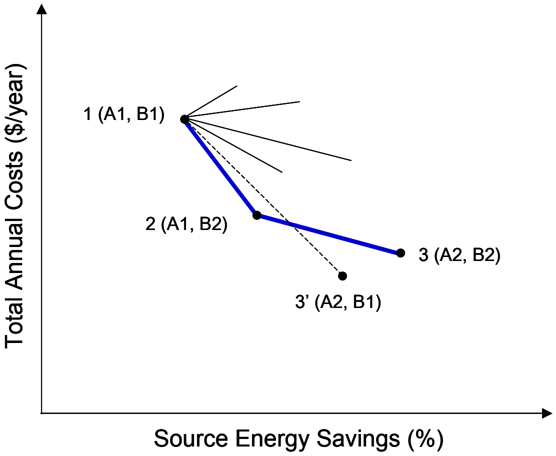

Figure 10. Illustration of a large-step special case

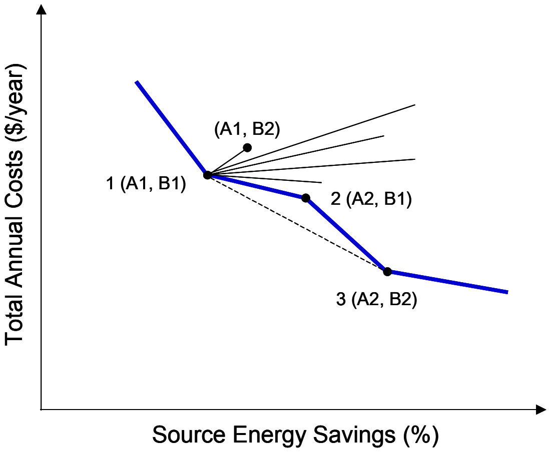

Figure 11. Illustration of a positive interaction special case

The sequential search technique will select positively interacting options if one of the options is first individually selected (as shown in Figure 11); then the process may continue in a bootstrapping fashion. However, it is also possible that neither option will be selected by itself, which makes it impossible for the bootstrapping process to begin or continue. This is a potential shortcoming of the sequential search technique. One possibility is for the user to identify potential synergies and develop combined options so the synergistic options are evaluated together.

5. Sample Least-Cost System Optimization Results

Figure 12 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).

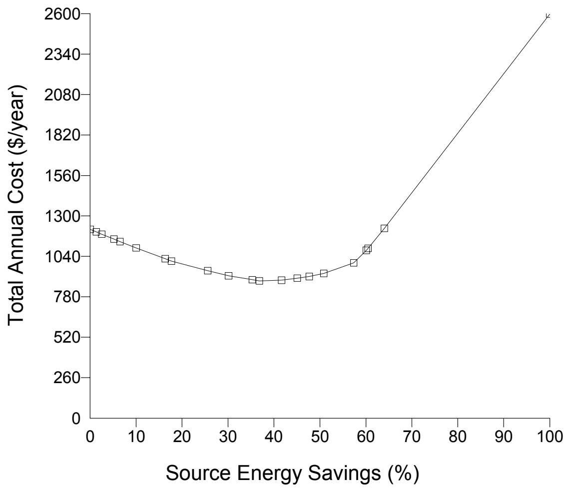

Figure 12. Sample system optimization results showing least-cost system curve

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 12 is shown in Figure 13. Each symbol represents a particular simulation in the optimization search with different search iterations indicated by different colors. *BEopt* 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.

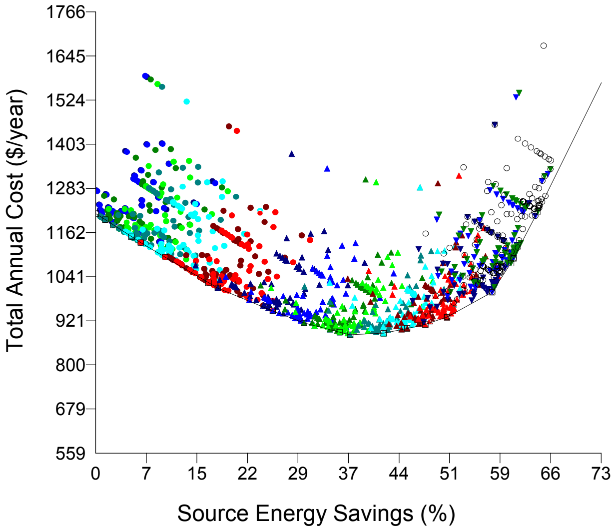

Figure 13. Close-up of sample optimization results showing all points in the neighborhood of the least-cost curve

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. For example, depending upon the cost/performance starting point for a residential research project, it is possible for cost savings to increase more rapidly than predicted by the least-cost curve (Figure 14).

It is also possible for costs to increase more rapidly than predicted by the least-cost curve (Figure 15). Finally (Figure 16), system choices can in some cases increase cost and reduce energy savings.

In all cases, the trajectory of project performance relative to the least-cost curve can be used to quickly determine project progress relative to the "least cost" limit for a given performance level.

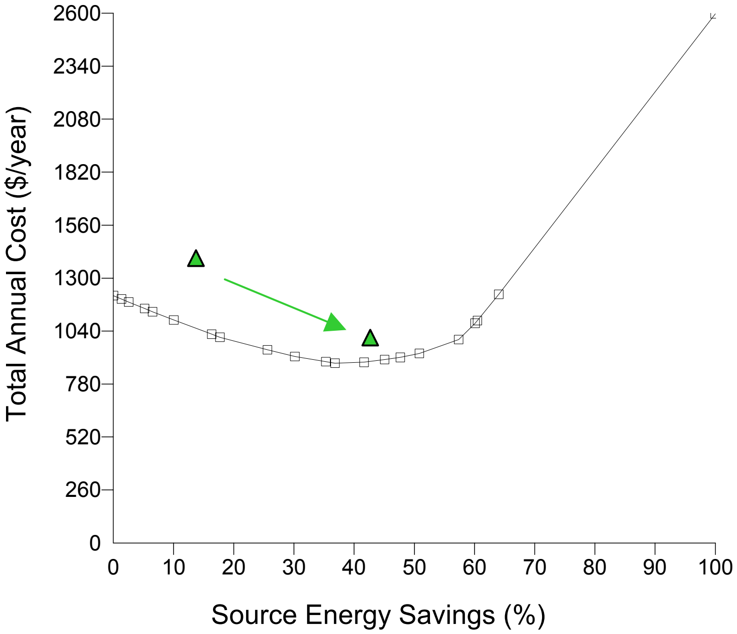

Figure 14. System cost savings can increase faster than the least-cost curve

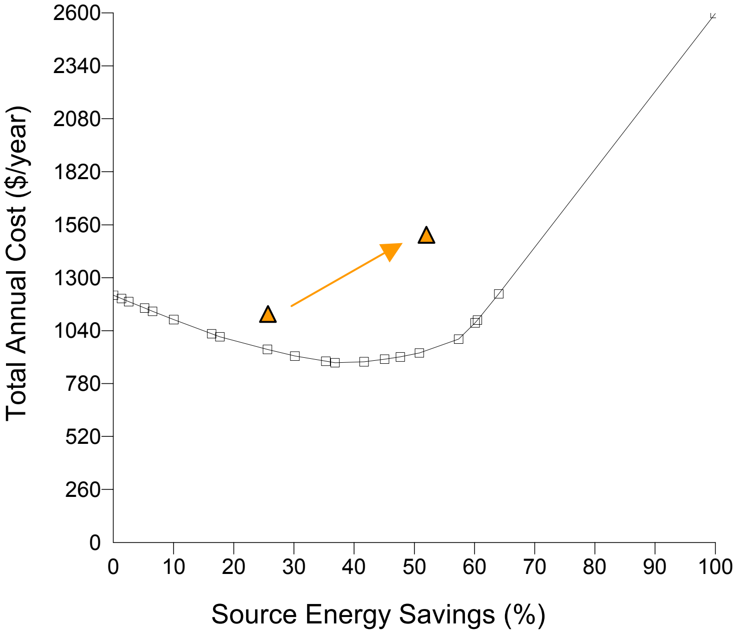

Figure 15. System costs may increase more rapidly than predicted by the least-cost curve

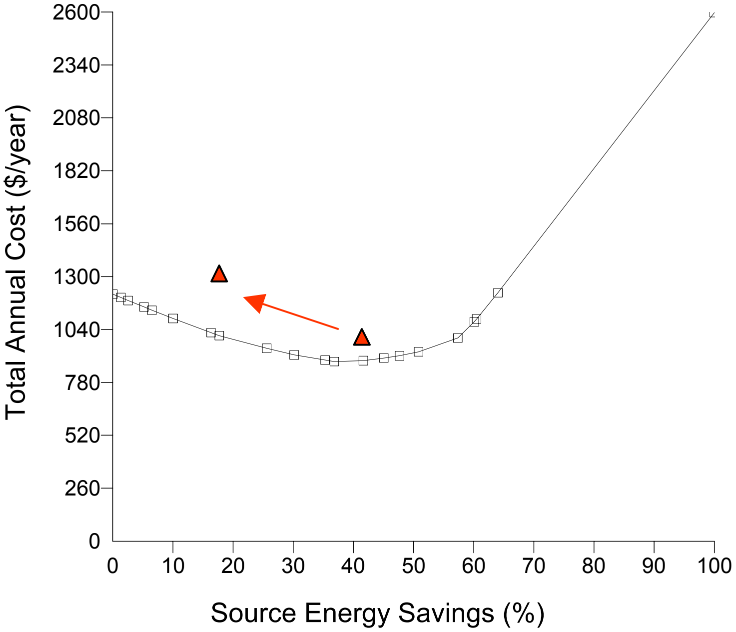

Figure 16. System costs may increase while source energy savings decrease

6. Overview of BEopt Inputs

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

6.1 Building Characteristics Considered in This Study

A simple two-story 1,800-ft^2 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., a basement in Chicago, slab on grade in 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 away to the north and south provide shading of side walls. 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.

6.2 Occupancy/Operational Assumptions

Occupancy and operational assumptions are as defined in the Building America Research Benchmark [1] and include time-of-day profiles for occupancy, appliance and plug loads, lighting, domestic hot water use, ventilation, and thermostat settings.

6.3 Base Case Building

Results are calculated relative to a base case building for each climate. Base case buildings are as defined in the Building America 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 [1].

6.4 Cost Assumptions

Each option has an assumed first cost and lifetime (see Appendix A). 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 multiplied by ceiling area by *BEopt*). 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 *BEopt* will calculate the differences between option costs.

Construction costs (wall insulation, ceiling insulation, foundation insulation, etc.) are typically based on R.S. Means [14] cost estimates. 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 costs[8]. 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 3).

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[8] 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. [15]

Table 3. 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 BEopt cost estimates used in this study do not include the initial costs required to re-engineer home designs[9], 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.

7. 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 mixed-humid, cold, hot-humid, hot dry, and marine climates respectively (Figure 5).

7.1 Least-Cost Path to Zero Net Energy

Figure 17 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 Building America Benchmark house definition. Out of all of the different possible combinations of options considered in the *BEopt* sequential search process, the points shown in Figure 17 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.

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[9] 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.

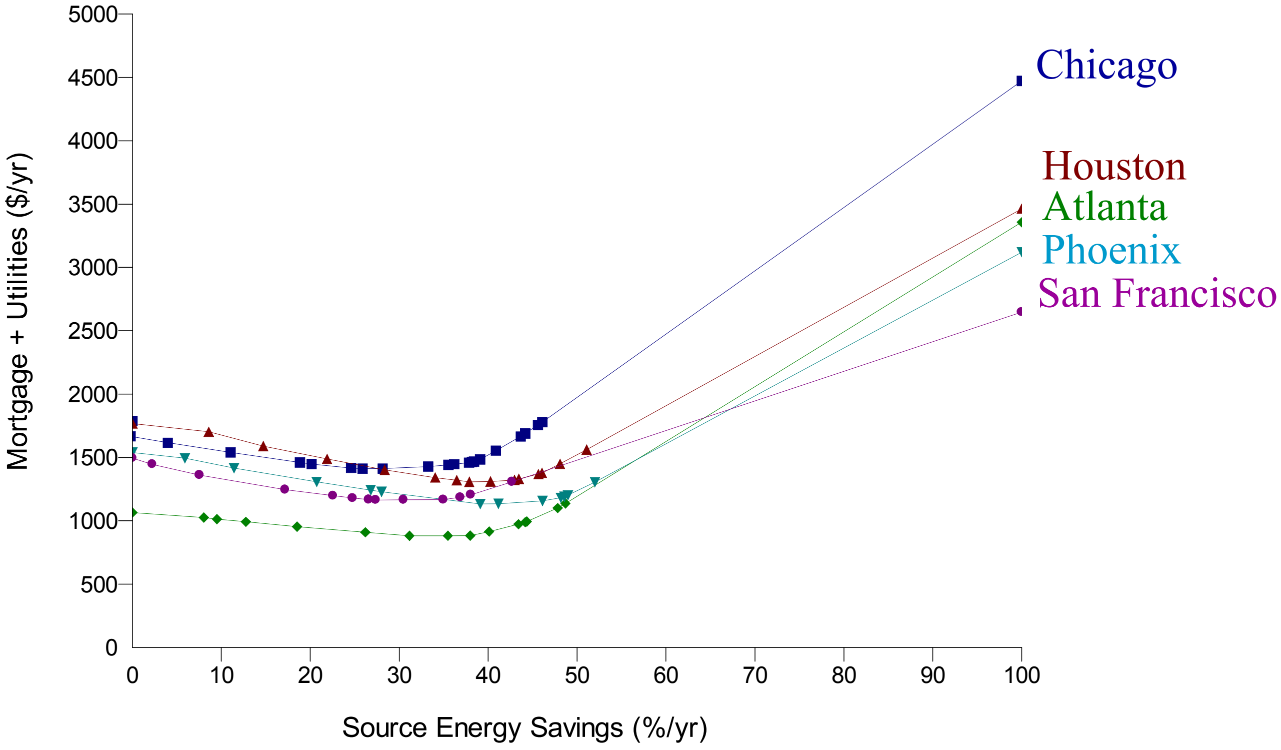


Figure 17. Least-cost curves for five cities

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 4.

Table 4. 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

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.

7.2 Recommended Investments in Efficiency for Homes with Integrated Onsite Power Systems

Figure 18 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 along with 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-ft^2 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 5.

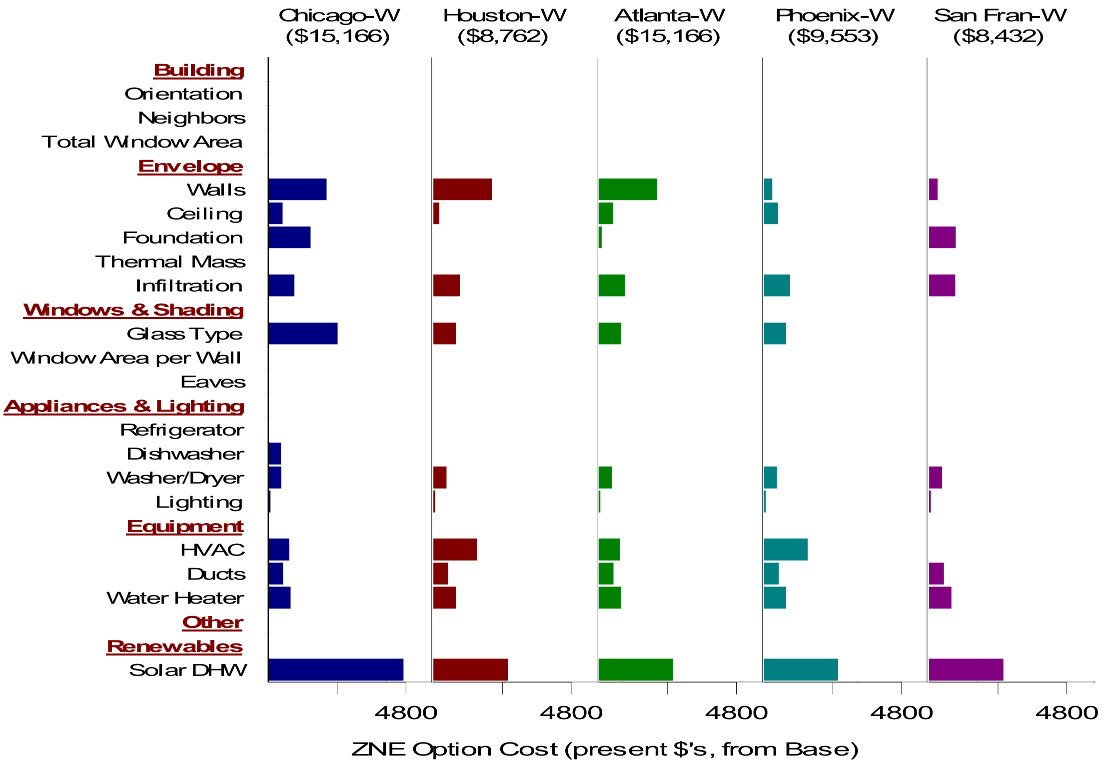


Figure 18. Present value of efficiency options ($) at the crossover point for investment in onsite power

Table 5. 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 6. Cost Multiplier Required to Reach ZNE Relative to Minimum Cost Point

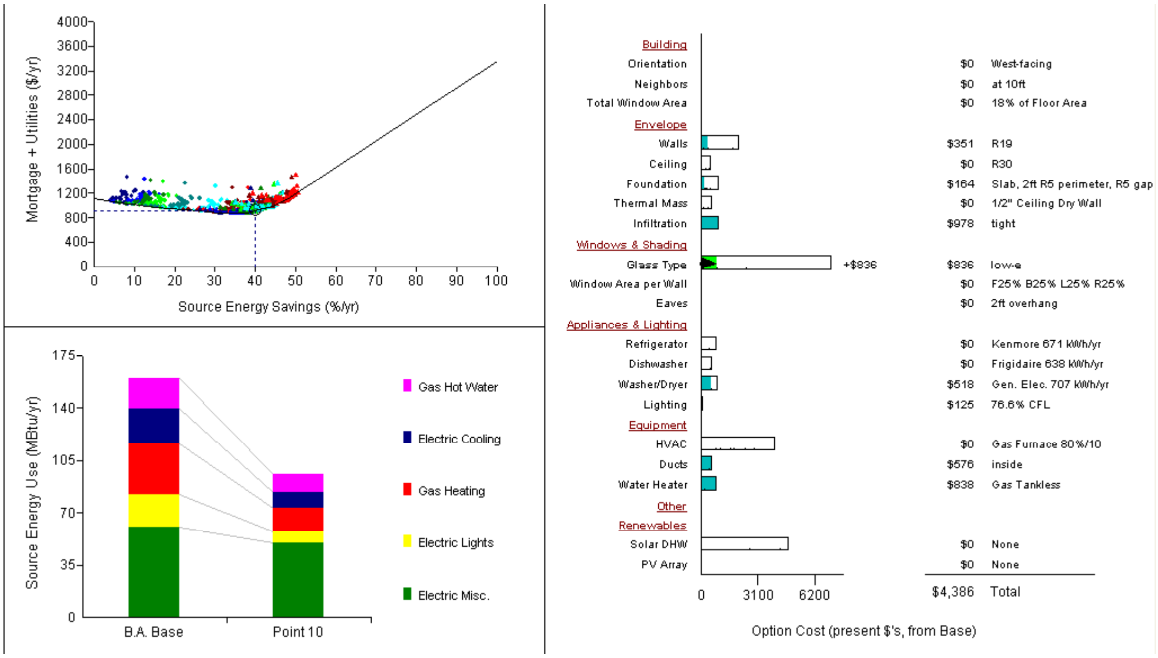
Location	Minimum Cost ($)	ZNE Cost ($)	Ratio
Atlanta	1,749	52,351	30
Chicago	3,899	71,874	18
Houston	2,585	56,759	22
Phoenix	2,585	49,679	19
San Francisco	1,337	42,808	32

Based on a review of the location of the crossover points shown in Table 5 and the cost ratios shown in Table 6, 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 Building America over the next several years.

8. BEopt Design/Technology Options for 40% Energy Savings in Five Climates

Figures 19-23 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 7. 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 7 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 19 - 23 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 19-23 to show the additional system solutions that are available in the near neighborhood of the least-cost curve.



Building		
Orientation	$0	West-facing
Neighbors	$0	at 10ft
Total Window Area	$0	18% of Floor Area
Envelope		
Walls	$351	R19
Ceiling	$0	R30
Foundation	$164	Slab, 2ft R5 perimeter, R5 gap
Thermal Mass	$0	1/2" Ceiling Dry Wall
Infiltration	$978	tight
Windows & Shading		
Glass Type	$836	low-e
Window Area per Wall	$0	F25% B25% L25% R25%
Eaves	$0	2ft overhang
Appliances & Lighting		
Refrigerator	$0	Kenmore 671 kWh/yr
Dishwasher	$0	Frigidaire 638 kWh/yr
Washer/Dryer	$518	Gen. Elec. 707 kWh/yr
Lighting	$125	76.6% CFL
Equipment		
HVAC	$0	Gas Furnace 80%/10
Ducts	$576	inside
Water Heater	$838	Gas Tankless
Other		
Renewables		
Solar DHW	$0	None
PV Array	$0	None
	$4,386	Total

Figure 19. Atlanta 40% savings point

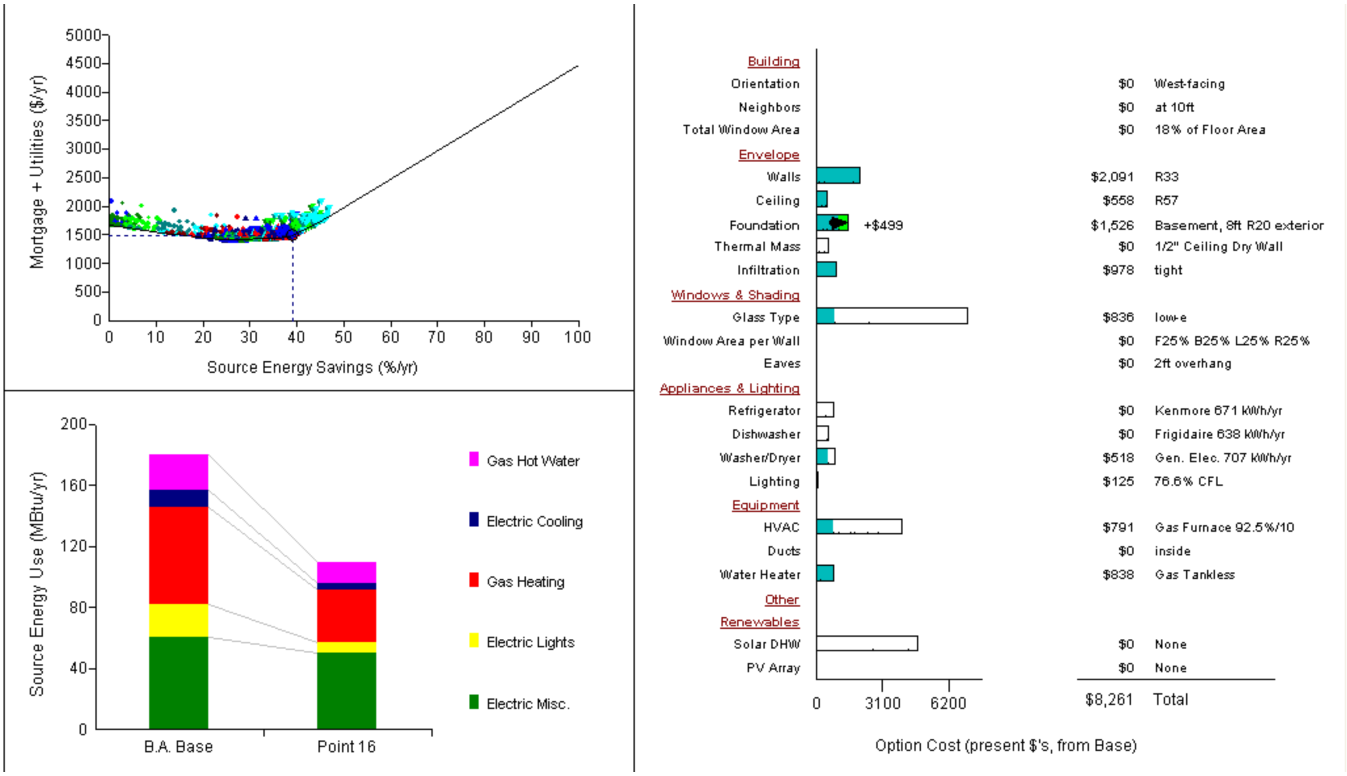


Figure 20. Chicago 40% savings point

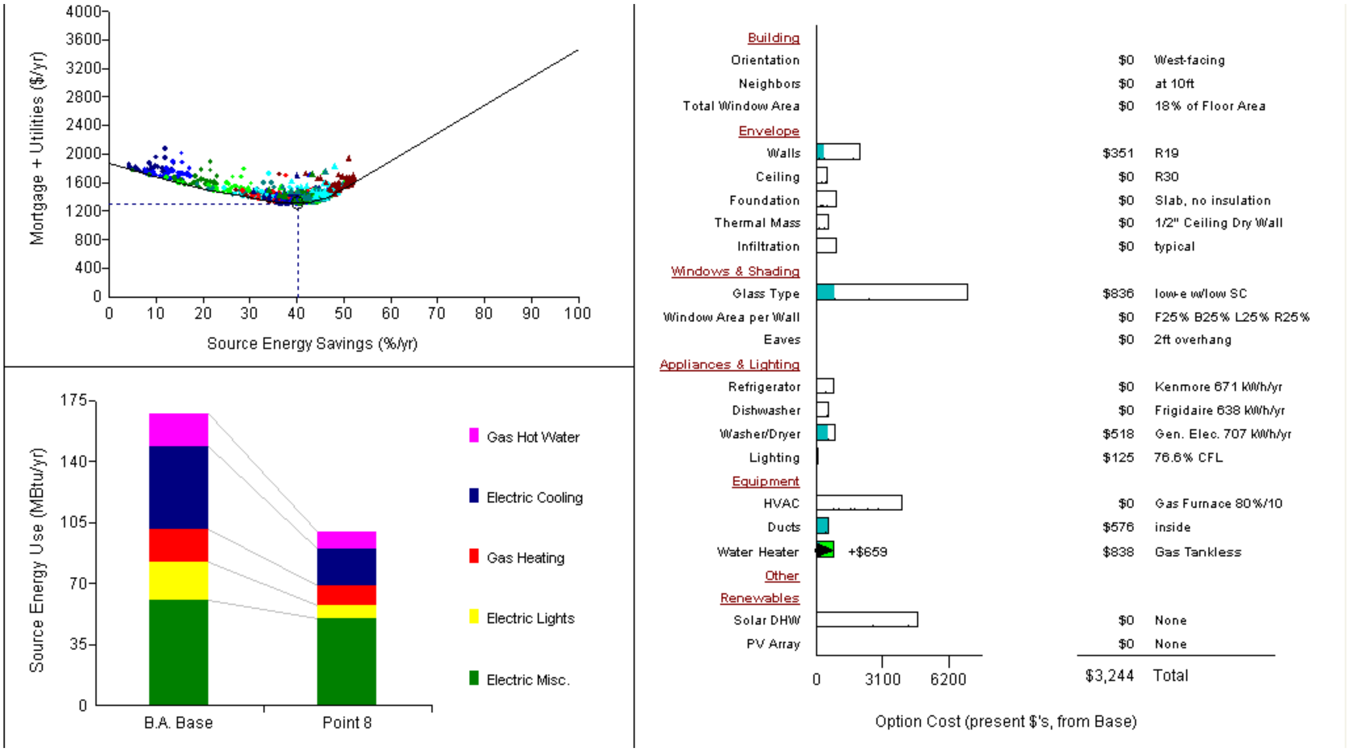
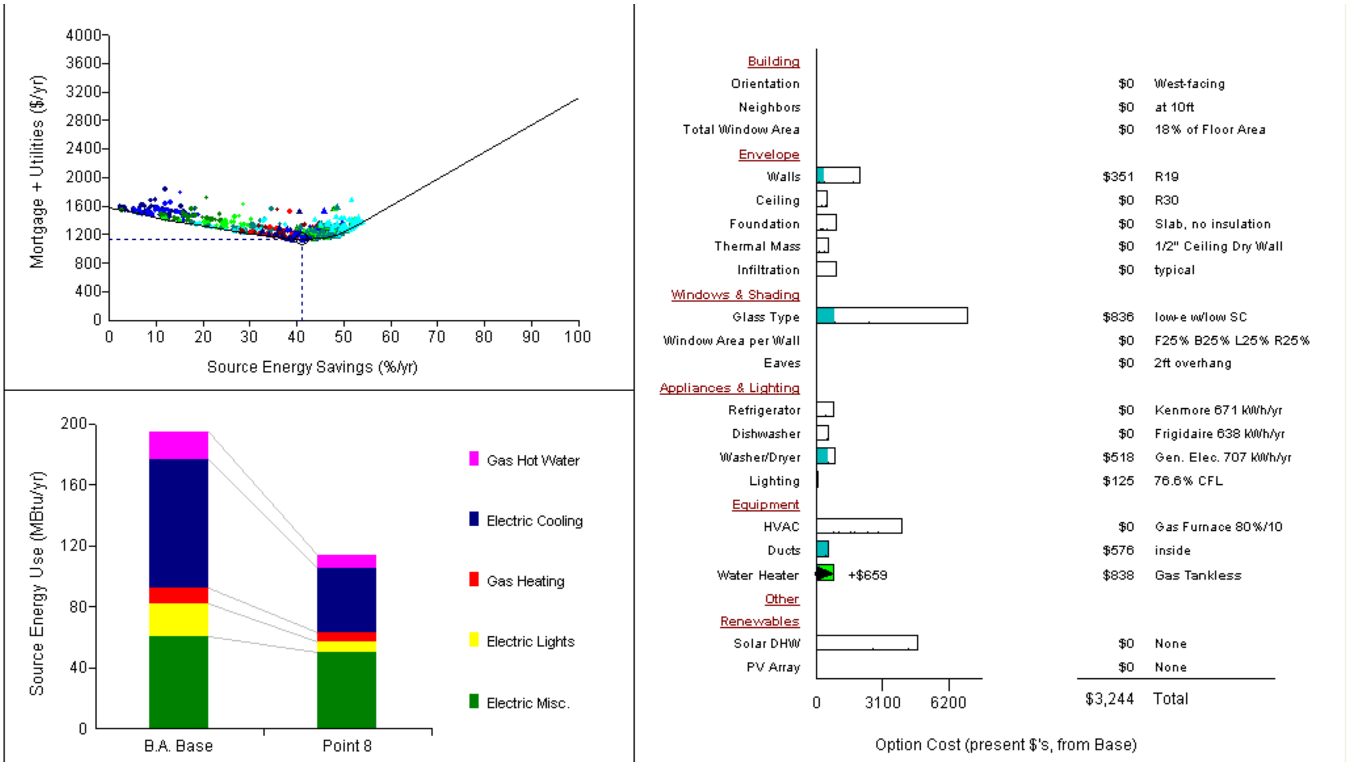
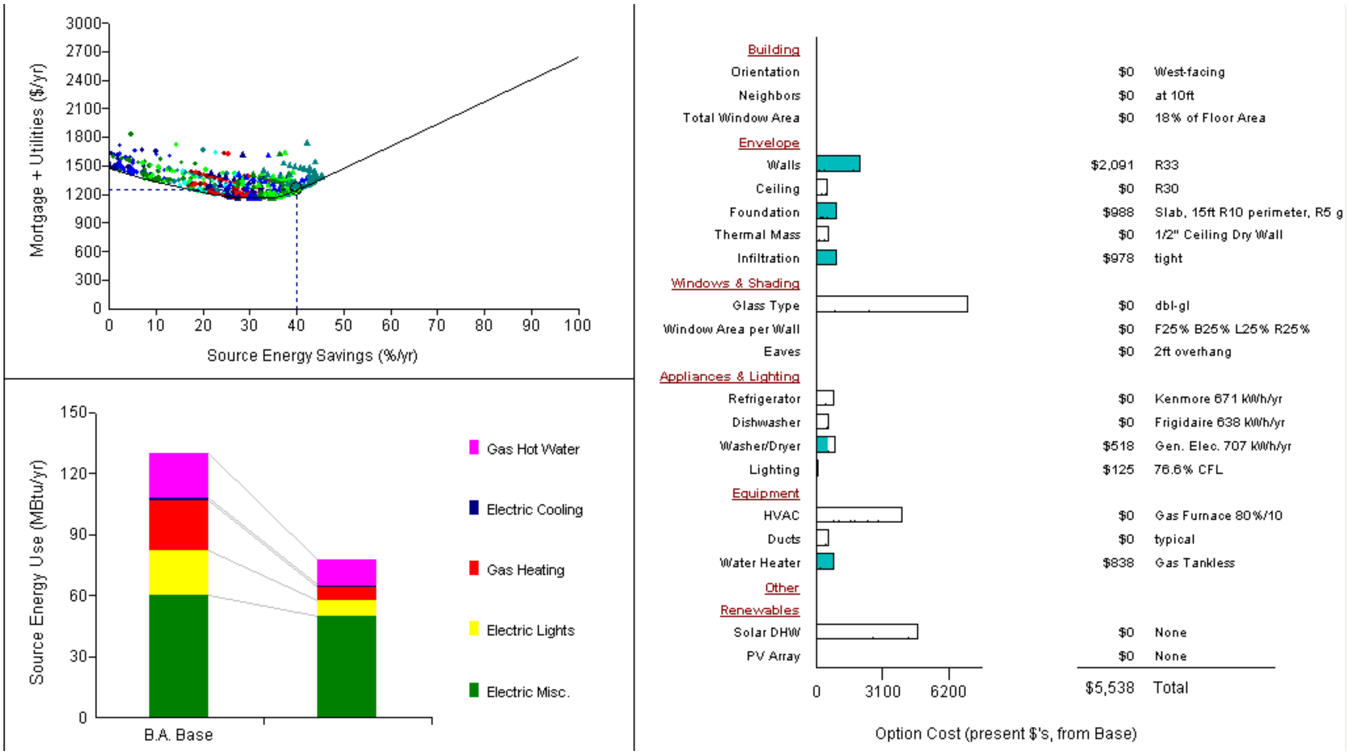


Figure 21. Houston 40% savings point



Building		
Orientation	$0	West-facing
Neighbors	$0	at 10ft
Total Window Area	$0	18% of Floor Area
Envelope		
Walls	$351	R19
Ceiling	$0	R30
Foundation	$0	Slab, no insulation
Thermal Mass	$0	1/2" Ceiling Dry Wall
Infiltration	$0	typical
Windows & Shading		
Glass Type	$836	low-e w/low SC
Window Area per Wall	$0	F25% B25% L25% R25%
Eaves	$0	2ft overhang
Appliances & Lighting		
Refrigerator	$0	Kenmore 671 kWh/yr
Dishwasher	$0	Frigidaire 638 kWh/yr
Washer/Dryer	$518	Gen. Elec. 707 kWh/yr
Lighting	$125	76.6% CFL
Equipment		
HVAC	$0	Gas Furnace 80%/10
Ducts	$576	inside
Water Heater	$838	Gas Tankless
Other		
Renewables		
Solar DHW	$0	None
PV Array	$0	None
	$3,244	Total

Figure 22. Phoenix 40% savings point



Building		
Orientation	$0	West-facing
Neighbors	$0	at 10ft
Total Window Area	$0	18% of Floor Area
Envelope		
Walls	$2,091	R33
Ceiling	$0	R30
Foundation	$988	Slab, 15ft R10 perimeter, R5 g
Thermal Mass	$0	1/2" Ceiling Dry Wall
Infiltration	$978	tight
Windows & Shading		
Glass Type	$0	dbl-gl
Window Area per Wall	$0	F25% B25% L25% R25%
Eaves	$0	2ft overhang
Appliances & Lighting		
Refrigerator	$0	Kenmore 671 kWh/yr
Dishwasher	$0	Frigidaire 638 kWh/yr
Washer/Dryer	$518	Gen. Elec. 707 kWh/yr
Lighting	$125	76.6% CFL
Equipment		
HVAC	$0	Gas Furnace 80%/10
Ducts	$0	typical
Water Heater	$838	Gas Tankless
Other		
Renewables		
Solar DHW	$0	None
PV Array	$0	None
	$5,538	Total

Figure 23. San Francisco 40% savings point

Table 7. 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

9. Sensitivity of Least-Cost Curve to Changes in Component Performance

The impact of changes in PV system costs on the least-cost curve for Phoenix are shown in Figures 24 and 25 for PV costs (including installation and O&M and replacement costs over a 30-year life) of $6, $9, and $12 per peak Watt. Assuming that PV costs change over time without changes in other component costs, the location of the crossover point on the least-cost curve from energy efficiency to onsite power shifts from 60% to 50% as overall PV costs decrease from $12/W to $6/W (Figure 26). Subject to the same assumption described above, as PV costs reach $9/W, investments in PV are more cost effective than investments in high-performance refrigerators and dishwashers (Figure 27). As PV costs begin to reach $6/W without changes in the cost of other components, investments in PV become more cost effective than investments in solar DHW, high performance AC equipment, and high-performance walls. It is important to note that it is extremely unlikely that other component costs would remained fixed over the time frame required for PV costs to reach $6/W. This example is included in this study to demonstrate that least-cost system choices for high-performance homes in the area of the crossover point will be extremely sensitive to the final cost/performance of future efficiency and onsite power components.

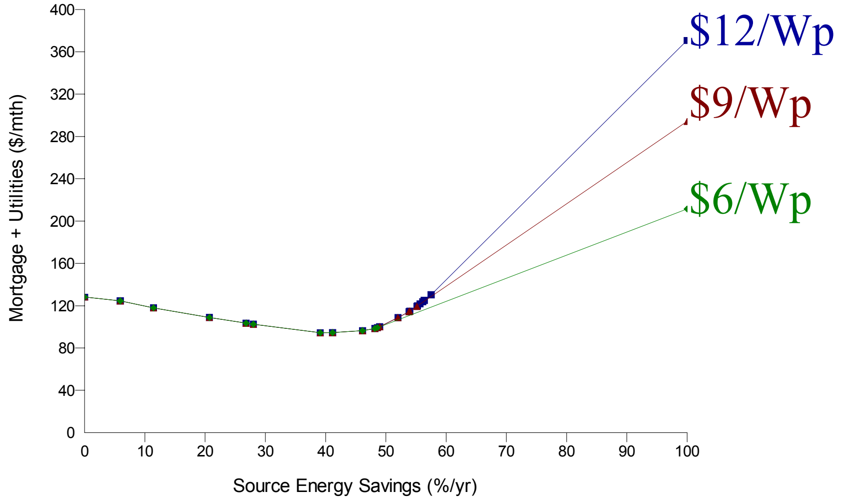


Figure 24. Impact of changes in PV cost on least-cost curve in Phoenix

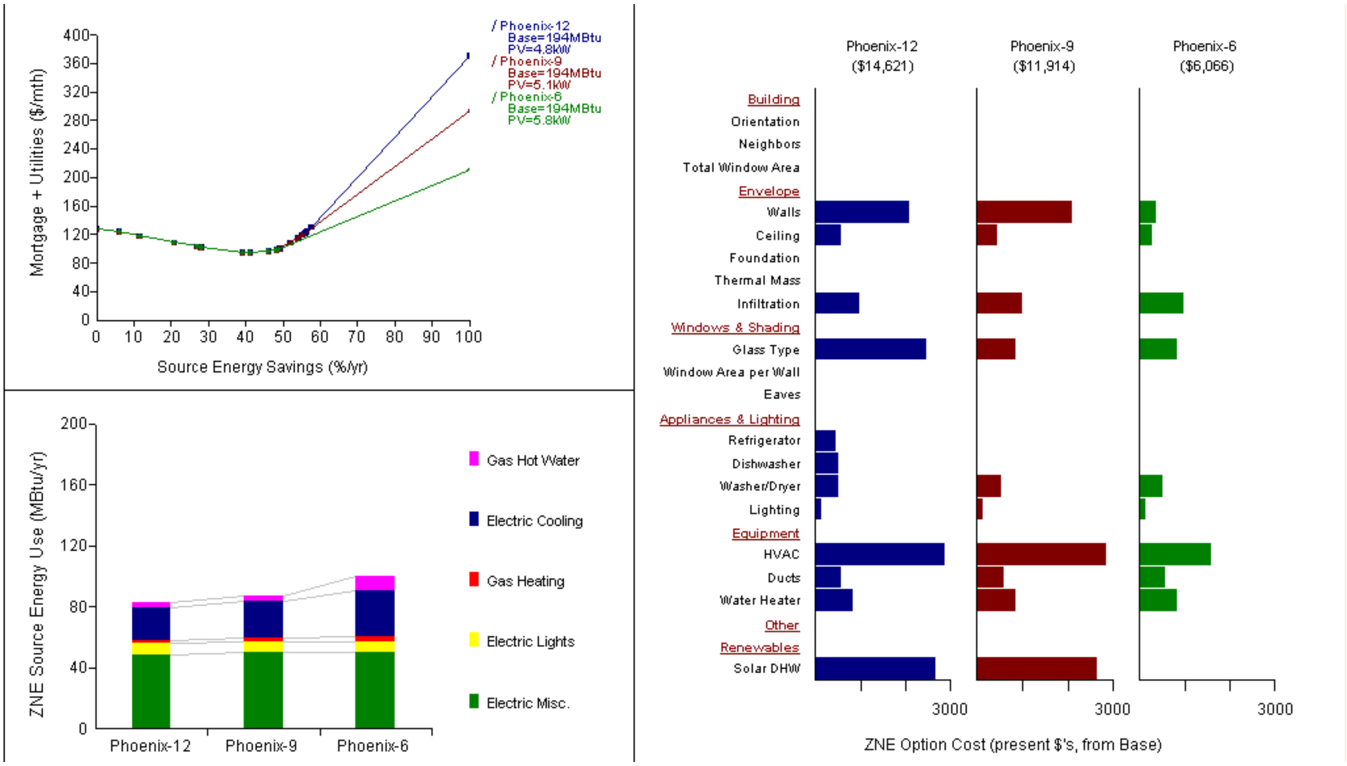


Figure 25. Impact of changes in PV cost on high-performance system options in Phoenix

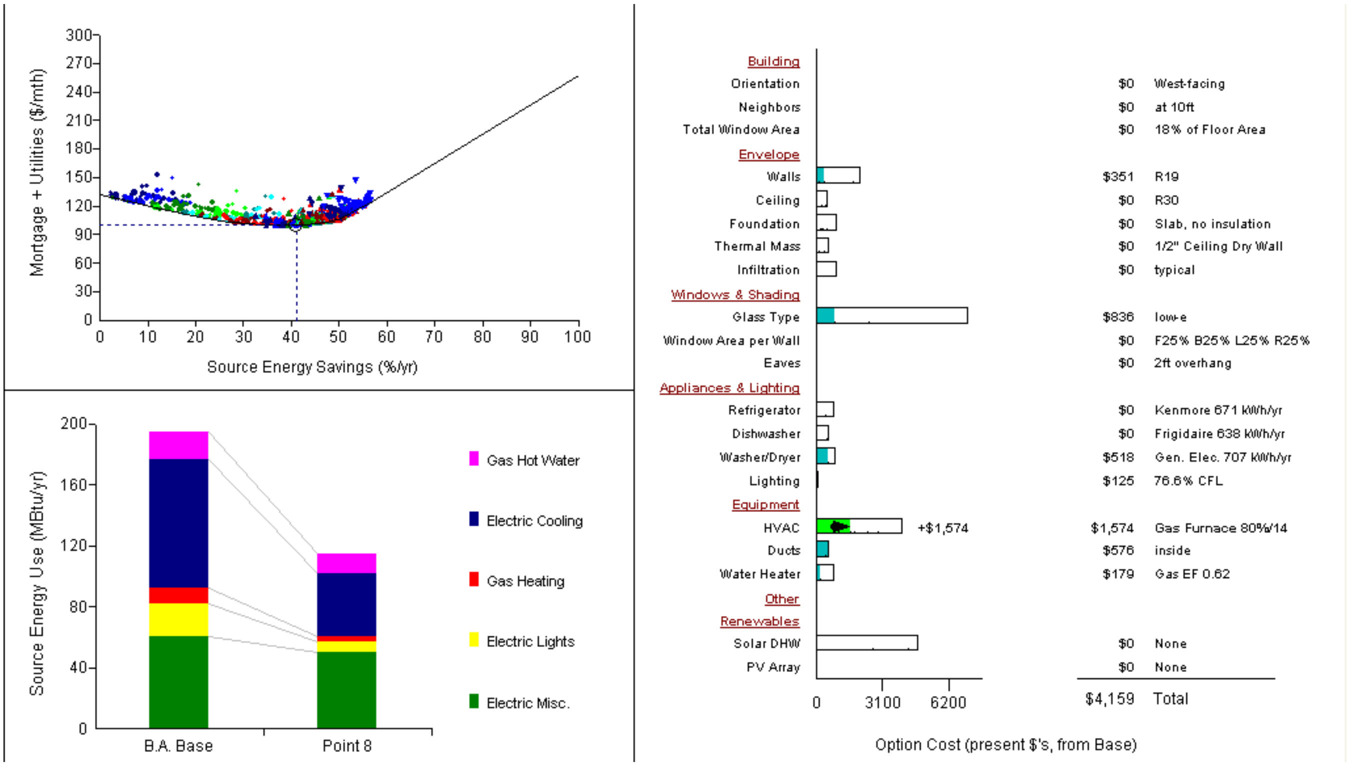


Figure 26. The 40% savings point for Phoenix without solar control glazing option

The least-cost curve is a characteristic of the house and its systems as a whole and is, therefore, not sensitive to the addition of a new component that increases energy savings unless the new component also reduces the marginal costs required to generate those energy savings relative to other system solutions. If a new component provides an alternative solution that is equivalent to existing solutions, the shape of the least-cost curve will not change. Because the least-cost curve is a system characteristic, the least-cost curve can be used as reference to determine the point at which a new component reaches or "breaks through" the current least-cost limit and provides new whole-house performance opportunities that did not previously exist. This point is illustrated in Figures 24 and 25 by examining the impact of the solar control glazing option on the least-cost curve in Phoenix. Without the solar-control glazing option, the least cost required to reach 40% savings is increased from $3,244 (Figure 22) to $4,159 (Figure 24). The shift in the least-cost curve provided by the solar control glazing option is shown in more detail in Figure 25.

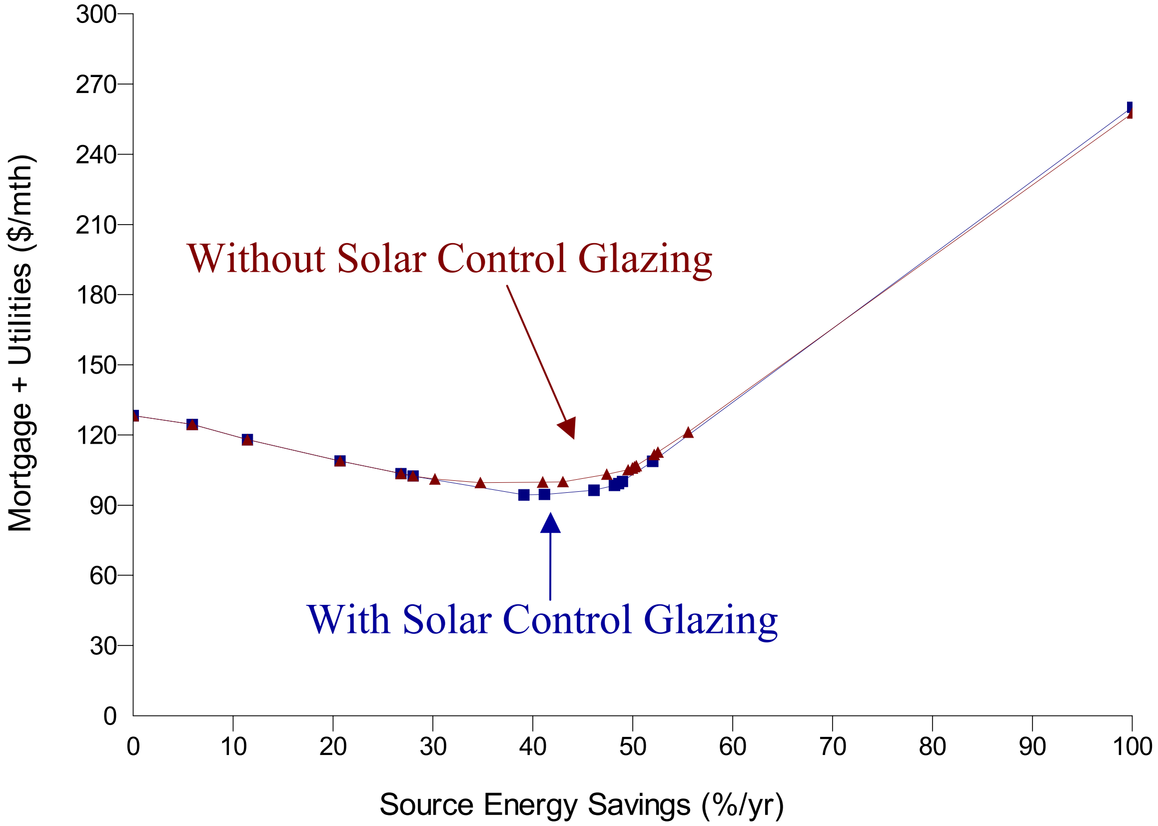


Figure 27. Impact of solar control glazing option on least-cost curve in Phoenix

10. Conclusions

The sequential search technique used in the *BEopt* analysis software 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 by *BEopt* 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, *BEopt* 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 Building America 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.

In addition to evaluating the cost/performance of specific design options, this study demonstrates that *BEopt* can be used to evaluate the impact that new components will have on the shape of the least-cost curve. Components that contribute to solutions that are equivalent to existing solutions will not change the shape of the least-cost curve. New components that move the least-cost curve down and to the right will be required to meet long term Building America performance goals. The results from this study will be used to identify the cost/performance characteristics required for future building components to successfully target energy savings levels greater than 50%.

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 Building America research teams.

11. 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.

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APPENDIX A. *BEopt* Cost and Performance Input Assumptions

As with any analysis study, the results of the analysis are subject to the assumptions used during the study. The cost and performance assumptions used in the present study are documented in this Appendix. These assumptions will be updated on a regular basis as new information becomes available from residential field studies. The use of specific manufacturer names in this Appendix does not represent an endorsement or recommendation for use of a specific product.

Table A.1. Utility and Onsite Power Inputs

Group	Input Variable	Value	Units
Economics	Electricity Source/Site Ratio	3	
	Electricity Cost	0.08275	\$/kWh
	Natural Gas Cost	1	\$/therm
	Discount Rate	0.05	
	Mortgage Interest Rate	0.07	
	Marginal Income Tax Rate	0.28	
	Analysis Period	30	years
	Net Metered Excess Sellback Rate	Local electric rate	\$/kWh
	Efficiency Cost Multiplier	1	
Photovoltaics	Module	Sharp NEH120E1	
	Installed Cost	7.5 (unless noted otherwise)	\$/rated W
	Derate Factor	Determined by location	%
	Daily Incident Solar	Determined by location	kWh/m^2
	Average System Efficiency	Determined by location	%

Table A.2. BEopt Building System Options

Group	Category	Included in Current Study	Option Name	Unit Cost		Total First Cost	Lifetime	Present Value
Building								
	Orientation							
			South-facing	$0.00		$0	30 years	$0
		x	West-facing	$0.00		$0	30 years	$0
			North-facing	$0.00		$0	30 years	$0
			East-facing	$0.00		$0	30 years	$0
	Neighbors							
			none	$0.00		$0	30 years	$0
			at 5 ft	$0.00		$0	30 years	$0
		x	at 10 ft	$0.00		$0	30 years	$0
			at 15 ft	$0.00		$0	30 years	$0
	Total Window Area							
			16% of Floor Area	$0.00		$0	30 years	$0
		x	18% of Floor Area	$0.00		$0	30 years	$0
			20% of Floor Area	$0.00		$0	30 years	$0
Envelope								
	Walls (1596 ft^{2})							
		x	R11	$3.37	/ft^{2}	$5,379	30 years	$5,379
		x	R13	$3.43	/ft^{2}	$5,474	30 years	$5,474
		x	R19	$3.59	/ft^{2}	$5,730	30 years	$5,730
		x	R26	$4.46	/ft^{2}	$7,118	30 years	$7,118
		x	R33	$4.68	/ft^{2}	$7,469	30 years	$7,469
	Ceiling (900 ft^{2})							
		x	R30	$1.00	/ft^{2}	$900	30 years	$900
		x	R41	$1.30	/ft^{2}	$1,170	30 years	$1,170
		x	R49	$1.48	/ft^{2}	$1,332	30 years	$1,332
		x	R57	$1.62	/ft^{2}	$1,458	30 years	$1,458
	Foundation (120 ft)							
		x	Slab, no insulation	$0.00	/ft	$0	30 years	$0
		x	Slab, 2-ft R5 perimeter, R5 gap	$1.37	/ft	$164	30 years	$164

Table A.2 – BEopt Building System Options (continued)

Group	Category	Included in Current Study	Option Name	Unit Cost		Total First Cost	Lifetime	Present Value
Envelope	Foundation (120 ft)	x	Slab, 4-ft R5 perimeter, R5 gap	$2.36	/ft	$283	30 years	$283
		x	Slab, 2-ft R10 perimeter, R5 gap	$2.21	/ft	$265	30 years	$265
		x	Slab, 4-ft R10 perimeter, R5 gap	$3.92	/ft	$470	30 years	$470
		x	Slab, 15-ft R10 perimeter, R5 gap	$8.23	/ft	$988	30 years	$988
		x	Basement, no insulation	$0.00	/ft	$0	30 years	$0
		x	Basement, 4-ft R5 exterior	$2.48	/ft	$298	30 years	$298
		x	Basement, 4-ft R10 exterior	$4.28	/ft	$514	30 years	$514
		x	Basement, 8-ft R10 exterior	$8.56	/ft	$1,027	30 years	$1,027
		x	Basement, 8-ft R15 exterior	$12.40	/ft	$1,488	30 years	$1,488
		x	Basement, 8-ft R20 exterior	$12.72	/ft	$1,526	30 years	$1,526
			Crawl Space, no insulation	$0.00	/ft	$0	30 years	$0

Table A.2 – BEopt Building System Options (continued)

Group	Category	Included in Current Study	Option Name	Unit Cost		Total First Cost	Lifetime	Present Value
Envelope	Foundation (120 ft)		Crawl Space, vented, R19 floor insulation	$0.00	/ft	$0	30 years	$0
			Crawl Space, R10 interior	$0.00	/ft	$0	30 years	$0
	Thermal Mass (1800 ft^2)							
		x	1/2-in. Ceiling Dry Wall	$0.19	/ft^2	$342	30 years	$342
			5/8-in. Ceiling Dry Wall	$0.26	/ft^2	$468	30 years	$468
			2 x 1/2-in. Ceiling Dry Wall	$0.38	/ft^2	$684	30 years	$684
			2 x 5/8-in. Ceiling Dry Wall	$0.52	/ft^2	$936	30 years	$936
	Infiltration							
		x	typical	$0.00		$0	30 years	$0
		x	tight	$978.00		$978	30 years	$978
Windows and Shading								
	Glass Type (324 ft^2)							
		x	dbl-gl	$20.91	ft^2	$6,775	30 years	$6,775
		x	low-e	$23.49	ft^2	$7,611	30 years	$7,611
		x	low-e w/low SC	$23.49	ft^2	$7,611	30 years	$7,611
		x	HM88	$28.55	ft^2	$9,250	30 years	$9,250
		x	HMTC88	$28.55	ft^2	$9,250	30 years	$9,250
		x	HM77	$28.55	ft^2	$9,250	30 years	$9,250
		x	HMSC75	$28.55	ft^2	$9,250	30 years	$9,250
		x	HM66	$28.55	ft^2	$9,250	30 years	$9,250
		x	HM55	$28.55	ft^2	$9,250	30 years	$9,250
		x	HM44	$28.55	ft^2	$9,250	30 years	$9,250
		x	HM33	$28.55	ft^2	$9,250	30 years	$9,250
		x	HM22	$28.55	ft^2	$9,250	30 years	$9,250
		x	Insol8	$42.83	ft^2	$13,877	30 years	$13,877

Table A.2 – BEopt Building System Options (continued)

Group	Category	Included in Current Study	Option Name	Unit Cost	Total First Cost	Lifetime	Present Value
Windows and Shading							
	Window Area per Wall						
		x	F25% B25% L25% R25%	$0.00	$0	30 years	$0
			F25% B50% L12.5% R12.5%	$0.00	$0	30 years	$0
	Eaves						
			none	$0.00	$0	30 years	$0
			1-ft overhang	$320.00	$320	30 years	$320
		x	2-ft overhang	$490.00	$490	30 years	$490
			3-ft overhang	$670.00	$670	30 years	$670
Appliances and Lighting							
	Refrigerator						
		x	Kenmore 671 kWh/yr	$1,099.00	$1,099	15 years	$1,628
		x	Kenmore 606 kWh/yr	$1,399.00	$1,399	15 years	$2,072
		x	Kenmore 572 kWh/yr	$1,699.00	$1,699	15 years	$2,516
	Dishwasher						
		x	Frigidaire 638 kWh/yr	$299.00	$299	10 years	$595
		x	Frigidaire 489 kWh/yr	$549.00	$549	10 years	$1,093
		x	Gen. Elec. 477 kWh/yr	$599.00	$599	10 years	$1,192

Table A.2 – BEopt Building System Options (continued)

Group	Category	Included in Current Study	Option Name	Unit Cost		Total First Cost	Lifetime	Present Value
Appliances and Lighting								
	Washer/Dryer							
		x	Gen. Elec. 2316 kWh/yr	$399.00		$399	15 years	$591
		x	Gen. Elec. 707 kWh/yr	$749.00		$749	15 years	$1,109
		x	Maytag 693 kWh/yr	$1,029.00		$1,029	15 years	$1,524
	Lighting (29 lamps)							
		x	10% CFL	$1.41	/lamp	$41	5 years	$145
		x	23.3% CFL	$1.79	/lamp	$52	5 years	$184
		x	76.6% CFL	$2.62	/lamp	$76	5 years	$270
			100% CFL	$2.86	/lamp	$83	5 years	$294
Equipment								
	HVAC							
		x	Gas Furnace 80%/10	$2,035.00		$2,035	15 years	$3,014
		x	Gas Furnace 92.5%/10	$2,569.00		$2,569	15 years	$3,805
		x	Gas Furnace 80%/12	$2,717.00		$2,717	15 years	$4,024
		x	Gas Furnace 92.5%/12	$3,251.00		$3,251	15 years	$4,815
		x	Gas Furnace 80%/14	$3,098.00		$3,098	15 years	$4,588
		x	Gas Furnace 92.5%/14	$3,632.00		$3,632	15 years	$5,379
		x	Gas Furnace 80%V/14	$3,970.00		$3,970	15 years	$5,880

Table A.2 – BEopt Building System Options (continued)

Group	Category	Included in Current Study	Option Name	Unit Cost	Total First Cost	Lifetime	Present Value
Equipment							
	HVAC						
		x	Gas Furnace 94%V/14	$4,779.00	$4,779	15 years	$7,078
			Gas Furnace 80%V/18DS	$4,125.00	$4,125	15 years	$6,109
			Gas Furnace 94%V/18DS	$5,069.00	$5,069	15 years	$7,507
			Elec. Furn. 100%/10	$2,035.00	$2,035	15 years	$3,014
			Elec. Furn. 100%/12	$2,718.00	$2,718	15 years	$4,025
			Elec. Furn. 100%/14	$3,099.00	$3,099	15 years	$4,590
			Elec. Furn. 100%/17DS	$3,754.00	$3,754	15 years	$5,560
			Heat Pump 6.9/11.5	$2,459.00	$2,459	15 years	$3,642
			Heat Pump 7.3V/11.5	$2,823.00	$2,823	15 years	$4,181
			Heat Pump 8.3V/15.5	$4,137.00	$4,137	15 years	$6,127
			Heat Pump 7.6V/17DS	$4,399.00	$4,399	15 years	$6,515

Table A.2 – BEopt Building System Options (continued)

Group	Category	Included in Current Study	Option Name	Unit Cost	Total First Cost	Lifetime	Present Value
Equipment							
	Ducts						
		x	typical	$810.00	$810	30 years	$ 810
		x	improved	$1,242.00	$1,242	30 years	$1,242
		x	inside[10]	$1,386.00	$1,386	30 years	$1,386
	Water Heater						
		x	Gas EF 0.55	$465.00	$465	10 years	$926
		x	Gas EF 0.62	$555.00	$555	10 years	$1,105
		x	Gas Tankless	$886.00	$886	10 years	$1,764
			Elec. EF 0.86	$495.00	$495	10 years	$985
			Elec. EF 0.95	$585.00	$585	10 years	$1,165
			Elec. Tankless	$1,075.00	$1,075	10 years	$2,140
Other							
Renewables							
	Solar DHW						
		x	None	$0.00	$0	30 years	$0
		x	32 ft^2 ICS	$2,654.00	$2,654	30 years	$2,654
		x	40 ft^2 Flat Plate	$4,307.00	$4,307	30 years	$4,307
		x	64 ft^2 Flat Plate	$4,768.00	$4,768	30 years	$4,768

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[10] Ducts were assumed to be located inside the conditioned space in cold climates. All three duct locations were considered in other climates.

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The Building America residential systems research project uses an analysis-based system research approach to (1) Identify research priorities, (2) Identify technology gaps and opportunities, (3) Establish a consistent basis to track research progress, (4) Increase the cost effectiveness of research investments by identifying system solutions that are most likely to succeed as the initial targets for residential system research projects. This report describes the technical approach used by Building America to determine the most cost effective pathways to achieve whole-house energy savings goals. The report provides an overview of design/technology strategies leading to net zero energy buildings as the basis for analysis of future residential system performance. The analysis approach is demonstrated by providing an initial comparison of the least-cost options required to achieve 40% energy savings in five climate zones. The preliminary results from this study will be validated against field studies and updated on an annual basis to reflect best available residential system cost/performance data from ongoing Building America research activities.

15. SUBJECT TERMS
Building America; U.S. Department of Energy; residential homes; analysis-based research; cost-effective research; whole-house energy svings; cost/performance

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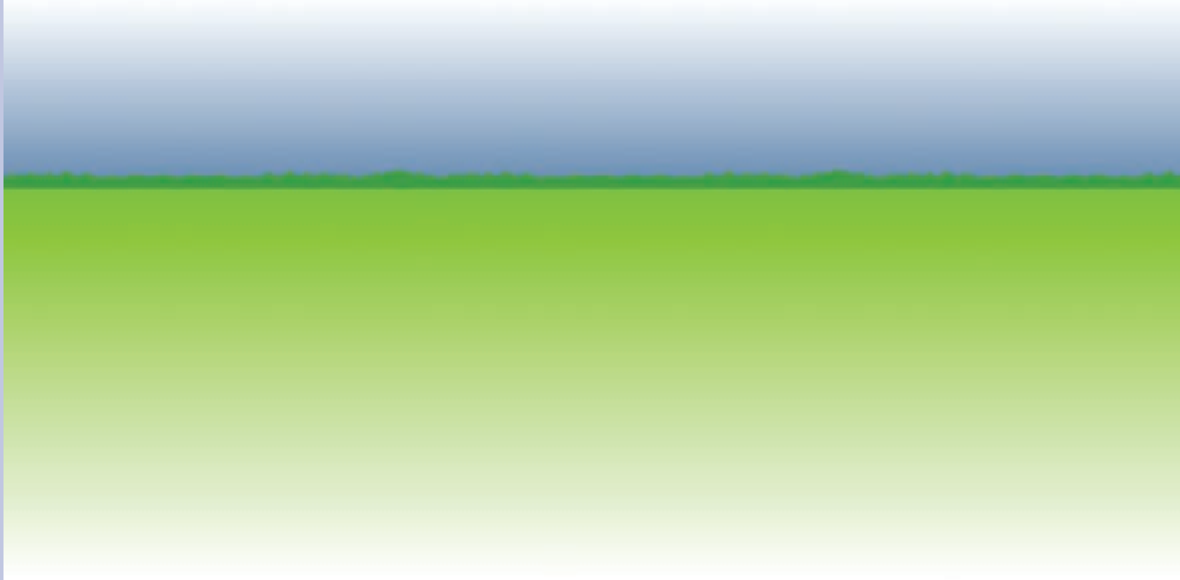

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