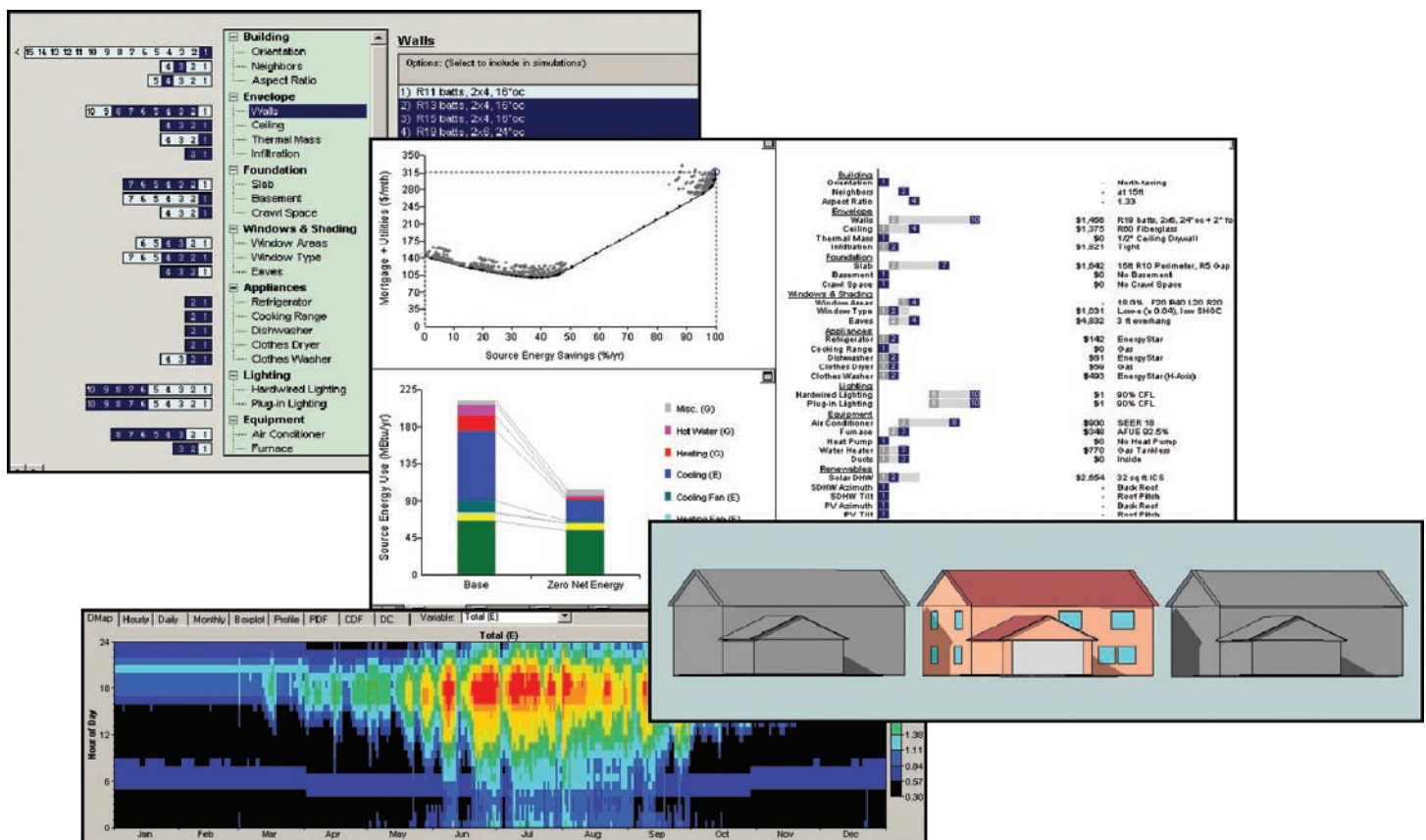# BEopt™ Software for Building Energy Optimization: Features and Capabilities

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BEopt™ Software for Building Energy Optimization: Features and Capabilities

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BEopt™ Software for Building Energy Optimization:

Features and Capabilities

Abstract

A zero net energy (ZNE) building produces as much energy as it uses on an annual basis, using a grid-tied, net-metered photovoltaic (PV) system and active solar. The optimal path to ZNE extends from a base case to the ZNE building through a series of energy-saving building designs with minimal energy-related costs.

The BEopt™ software is designed to find optimal building designs along the path to ZNE. A user selects from predefined options in various categories to specify options to be considered in the optimization. Energy savings are calculated relative to a reference. The reference can be either a user-defined base-case building or a climate-specific Building America Benchmark building automatically generated by the BEopt software. The user can also review and modify detailed information on all available options in a linked options library spreadsheet.

The BEopt software calls the DOE2 and TRNSYS simulation engines and uses a sequential search technique to automate the process of identifying optimal building designs along the path to ZNE. The BEopt software finds these optimal and near-optimal designs based on *discrete* building options reflecting realistic construction options. The BEopt software handles special situations with positive or negative interactions between options in different categories.

The BEopt software includes a results browser that allows the user to navigate among different design points and retrieve detailed results regarding energy end-use and option costs in different categories.

Multiple cases, based on a selected parameter such as climate, can be included in a BEopt project file for comparative purposes.

1. Background

1.1 Types of Zero Energy Buildings

Historically, fully autonomous zero energy buildings have been built independent of any connection to the utility grid. In a new approach, the zero *net* energy building promises more widespread applicability. The ZNE building uses grid-tied, net-metered PV and active solar to produce as much energy as it uses on an annual source-energy basis.

1.2 Source versus Site Energy Accounting

ZNE can be defined in terms of site energy (used at the building site) or source energy (sometimes called primary energy). Source energy provides a metric for assessing total energy use when dealing with multiple fuel types. From a societal point of view, source energy better reflects the overall consequences of energy use and is appropriate for ZNE buildings analysis. Source-to-site energy ratios depend somewhat on location and the specifics of what is included in the calculation. The user can enter specific values into the BEopt software. For electricity purchased from a utility, source energy accounts for power-plant generation efficiency and transmission

and distribution losses, and site-to-source ratios are typically about 3, depending on the mix of electrical generation types (coal-fired, natural-gas combined-cycle, nuclear, hydropower, etc.) For natural gas and propane, the source-to-site energy ratios are slightly greater than 1.

2. The Path to Zero Net Energy

Energy and cost results can be plotted in terms of annual energy-related costs (the sum of utility bills and mortgage payments for energy options) versus percent energy savings (Figure 1). The path to zero net energy extends from a base case (e.g., a current-practice building, a code-compliant building, or some other reference building) to a ZNE building with 100% energy savings. The optimal path is defined as the lower bound of results from all possible building designs (i.e., connecting minimal cost points for various levels of energy savings). Alternatively, net present value or other economic figures of merit could be shown on the y-axis.

Points of particular significance on the path (Figure 1) can be described as follows. From the base case at point 1, energy use is reduced by employing building efficiency options (e.g., improvements in wall R-value, furnace AFUE, air conditioner SEER, etc.) A minimum annual cost optimum occurs at point 2 (assuming the minimum does not occur at the base case). Additional building efficiency options are employed until the marginal cost of saved energy for these options equals the cost of producing PV energy at point 3. From that point on, energy savings are solely a result of adding PV capacity until ZNE is achieved at point 4.
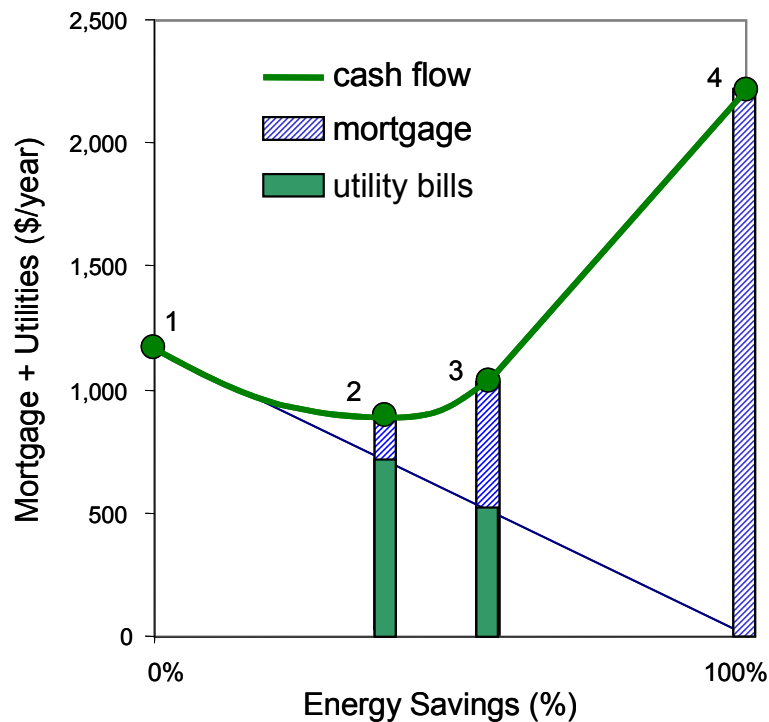

Fig. 1: Conceptual plot of the path to ZNE

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 [1].

With today's computer power, the bottleneck is no longer run times for individual simulations, 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, exhaustive enumeration run time is prohibitive for the millions of combinations that can result from options in, for example, ten or more categories.

Recently, several computer programs have been developed to automate building energy optimization. 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 [2]. GenOpt is a generic optimization program for use with various building energy simulation programs and user-selectable optimization methods [3].

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) that balances investments in efficiency versus utility bill savings. However, there are sometimes non-economic reasons for targeting a 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 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 could be used to represent that category in an optimization methodology (along with other discrete and continuous categories). After optimization, the discrete options closest to the optimal values could 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 ZNE or 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. Some such solutions can be identified by the optimization search technique, while others can be added with perturbation techniques.

4. BEopt Software

The BEopt software is a computer program designed to find optimal building designs along the path to ZNE and to accelerate the process of developing high-performance building designs. In addition to an optimization search, the BEopt software includes (1) a main input screen that allows the user to select, from many predefined options, those to be used in the optimization, (2) an output screen that allows the user to display detailed results for many optimal and near-optimal building designs, and (3) an options library spreadsheet that allows a user to review and modify detailed information on all available options. These BEopt interface components (inputs, library, and outputs) are the subject of this paper.

The main input screen allows a user to select from predefined options in various categories (e.g., wall type, ceiling type, window glass type, HVAC type, etc.) to specify options to be considered in the optimization. The user can also review and modify detailed information on all available options and the Building America Benchmark [4] in a linked options library spreadsheet.

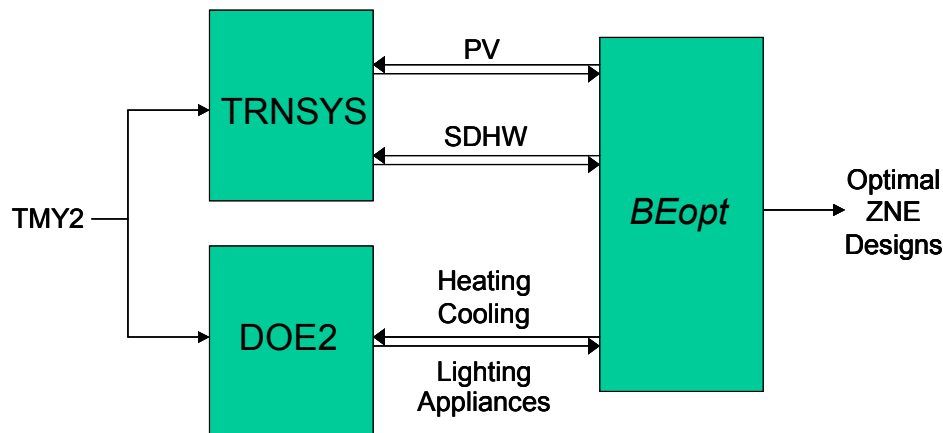The BEopt software calls the DOE2 [5] and TRNSYS [6] simulation engines. TMY2

Fig. 2: Optimization with multiple simulation programs

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weather data [7] are used for all simulations (Figure 2).

The DOE-2 simulation program is used to calculate energy use as a function of building-envelope options and HVAC equipment options. Appliance and lighting option energy savings are calculated based on energy-use intensity factors and schedules input into DOE2. The TRNSYS simulation program is used to calculate water-heating loads and energy savings for solar water heating. TRNSYS 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 [8] and the database of performance characteristics published on its Web site (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. A prototype version of the BEopt software using EnergyPlus [9] has demonstrated technical feasibility for future use of a single simulation engine with extended capabilities.

The BEopt software automates the process of identifying optimal building designs along the path to ZNE using a sequential search technique [10]. At each step along the path, the BEopt software runs a series of simulations incorporating each user-selected option one at a time and searches for the most cost-effective combination of options. The sequential search technique has several advantages. First, it finds intermediate optimal points along the entire path (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, providing realistic construction options. Third,

multiple near-optimal designs are identified at each particular energy-savings level, providing design alternatives.

The BEopt software has the ability to handle special situations caused by interactions between options. Special situations with negative interactions are handled by looking back along the path and continually re-evaluating previously rejected options (to properly identify the potential of large-savings options and options involving trade-offs between categories). Positive interactions between categories are accommodated by allowing the user to define combined options in the BEopt software (to ensure that such potentially synergistic combinations are evaluated during optimization).

Multiple user-defined cases can be included in a BEopt project file. Multiple cases are often used to analyze building performance as a function of climate. Cases can also be used to study how building performance is affected by economic parameters, PV-system characteristics, or the options selected for optimization. Up to 20 cases can be defined, with case tabs displayed along the bottom of the screen. Once an optimization has been completed, each case contains input screens and an output screen.

The main output screen includes a results browser that allows the user to navigate among the results associated with each (optimal and non-optimal) building design simulated during optimization. For each building design, the browser will display detailed results regarding energy consumption, costs, and options. If multiple cases exist in a project file, a Combined Graphs output screen will be available.

5. Options Library

The options library spreadsheet (Figure 3) contains detailed information for all the

BEopt categories and options. The options currently in the library are intended to represent readily available products and construction techniques. Whereas some users may only use the BEopt input screens to select from the currently available options, access to the options library allows the user to review and modify specific characteristics of each option such as energy properties and cost assumptions.

Each category worksheet lists the option numbers across the top of the screen. The Building America Benchmark is listed before the available options. The details of each category are grouped under three subtitles (General, Energy, and Economics).

In addition to constants input values, the spreadsheet includes many formulas. Option characteristics are converted to simulation input values. Climate-specific building characteristics are calculated for the Building America benchmark. Values in bold-faced type are linked to a summary worksheet and used in the simulation input files. Additional worksheets in the file allow access to the DOE2 and TRNSYS input files for more advanced users.

Each option has an assumed first cost and lifetime costs. Costs are retail and include national average estimated costs for hardware, installation labor, overhead, and profit. Some are input as unit costs that are

Fig. 3: Options library spreadsheet

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., the cost of solar water-heating systems). Inputs can also be based on total costs (e.g., the 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 user specified or based on national average cost data from sources such as R.S. Means [11] or California Database for Energy Efficient Resources [12]. Window and HVAC costs are based on quotes from manufacturers' distributors. Appliance costs

are based on manufacturers' suggested retail prices. In the future, the user will be able to select from amongst different cost assumptions for each option stored in a database.

Lifetimes for building construction options (wall insulation, ceiling insulation, foundation insulation, windows, etc.) are assumed to be 30 years. 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.

The BEopt Cost Combination Editor (Figure 4) can be used to develop user datasets of selected option costs (and lifetimes).

Cost Combination Editor - Default.bcc

File   View   Help

Walls	Selected Set Name	Selected Value	RS Means 2005 [$/sqft]	DEER (RS Means) [$/sqft]
R11 batts, 2x4, 16"oc	RS Means 2005	$6.68	$6.68	
R13 batts, 2x4, 16"oc	DEER (RS Means)	$6.65		$6.65
R15 batts, 2x4, 16"oc	DEER (RS Means)	$6.69		$6.69
R19 batts, 2x6, 24"oc	DEER (RS Means)	$6.78	$6.78	$6.78
R21 batts, 2x6, 24"oc	DEER (RS Means)	$6.81		$6.81
R11 batts, 2x4, 16"oc + 1" foam	RS Means 2005	$7.43	$7.43	
R13 batts, 2x4, 16"oc + 1" foam	DEER (RS Means)	$7.49		$7.49
R19 batts, 2x6, 24"oc + 1" foam	DEER (RS Means)	$7.42	$7.34	$7.42
R21 batts, 2x6, 24"oc + 1" foam	DEER (RS Means)	$7.46		$7.46
R19 batts, 2x6, 24"oc + 2" foam	RS Means 2005	$7.54	$7.54	

Ceiling	Selected Set Name	Selected Value	RS Means 2005 [$/sqft]	DEER [$/sqft]
R30 Fiberglass	RS Means 2005	$1.10	$1.10	$0.76
R40 Fiberglass	RS Means 2005	$1.47	$1.47	$0.86
R50 Fiberglass	RS Means 2005	$1.84	$1.84	
R60 Fiberglass	RS Means 2005	$2.20	$2.20	

Thermal Mass	Selected Set Name	Selected Value	RS Means 2005 [$/sq ft]	Home Depot 2005 [$/sq ft]
1/2" Ceiling Drywall	RS Means 2005	$0.60	$0.60	$0.57
5/8" Ceiling Drywall	RS Means 2005	$0.62	$0.62	$0.65
2 x 1/2" Ceiling Drywall	RS Means 2005	$1.20	$1.20	$1.14
2 x 5/8" Ceiling Drywall	RS Means 2005	$1.24	$1.24	$1.30

Close

Fig. 4: Option Cost Combinations Editor screen

6. Input Screens

6.1 Building Geometry

Some building geometry parameters (e.g., floor area, number of stories, roof characteristics, garage characteristics, etc.) are input via a dialog box (Figure 5). Other building geometry parameters (e.g., orientation, aspect ratio, window area per wall, eaves, and distance to neighboring buildings) are input as options available for optimization. House geometries based on BEopt user inputs can be rendered and displayed in either eQUEST [13] or SketchUp [14] (as shown in Figure 6, with neighboring houses for shading analysis).

6.2 Photovoltaic System Parameters

Some photovoltaic system parameters (e.g., module type, cost, de-rate factor, etc.) are input via a dialog box (Figure 5). Other photovoltaic system parameters (e.g., tilt, azimuth, and size) are input as options and are available for optimization. Tilt options can be specified relative to roof pitch or as absolute values. Azimuth options can be specified relative to house orientation or as absolute values. Size options can be specified relative to roof area or as absolute values.
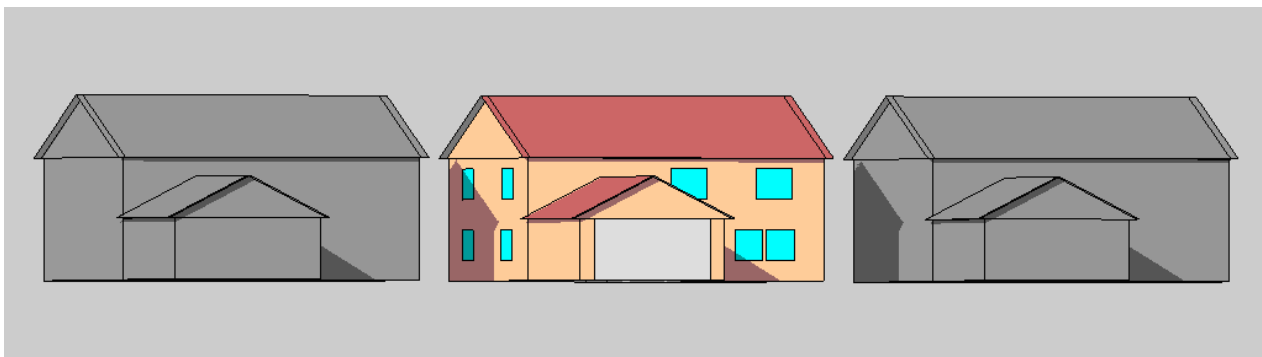

Fig. 5: Building and photovoltaic system input screen

Fig. 6: Sample of house geometry (with neighboring houses for shading analysis) based on user inputs in BEopt

6.3 Economic Parameters

Economic parameters (e.g., analysis period, inflation rate, discount rate, mortgage period, mortgage rate, down payment, income tax rate, utility rates, etc.) are input via a dialog box (Figure 7). Gas and electric utility rates can be selected as either national averages, state averages, or user specified with fixed- and marginal-cost components.

optimization. The summary matrix on the left side of the screen shows currently selected options by option number, and the estimated number of simulations and run time for the optimization are displayed. The radio button that is selected and highlighted in red designates the option included for the user-specified base case. Detailed information on all options can be viewed and modified by selecting the magnifying-glass button located at the upper-right corner

Fig. 7: Economics input screen

6.4 Energy-Saving Options

Upon opening a project file, the BEopt software scans the options library spreadsheet and loads categories and options associated with the project (Figure 8).

Option categories are divided into eight groups: Building, Envelope, Windows & Shading, Appliances & Lighting, Equipment, Renewables, Include Combinations, and Exclude Combinations. Selecting a category causes the options in that category to be listed in the display window. The user can then select options in each category to be included in the

of the options box. This will open the options library (described earlier).

A user may want to select only a single option in a particular category to specify a building characteristic. For example, if the building site dictates the building orientation as east, only the east option needs to be selected. However, if various orientations are possible, multiple options could be selected for the BEopt software to consider during optimization.

In other situations, subsets of options may be mutually exclusive. In the Foundation category, for example, options exist for slab-

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on-grade, crawl space, and basement configurations.

If slab-on-grade is the desired foundation type, only options of this type should be selected. Ultimately, the user chooses whether subsets of options should be treated as mutually exclusive or not. For example, should the optimization include all space-heating and water-heating equipment options (both gas and electric) or should only electric options or only gas options be considered? Performance characteristics of different options may also determine their selection (or de-selection). For instance, glazing types with low solar heat gain coefficients (SHGCs) may not be desired in a climate where passive solar heating is desirable.

Finally, the user is provided the ability to explicitly include or exclude certain combinations of options for evaluation. For example, if the user is interested in the interaction between south-facing glazing area and additional thermal mass, simply selecting available options within these two categories may not suffice. This is caused by the nature of the sequential search optimization technique – an option from either the thermal mass category or the glazing area category must first be independently cost-effective in order for the combination of additional thermal mass and glazing area to be evaluated by the BEopt software. However, if the user has the technical experience to recognize this situation, an Include Combinations category (for example, "Glass+Mass") can be created
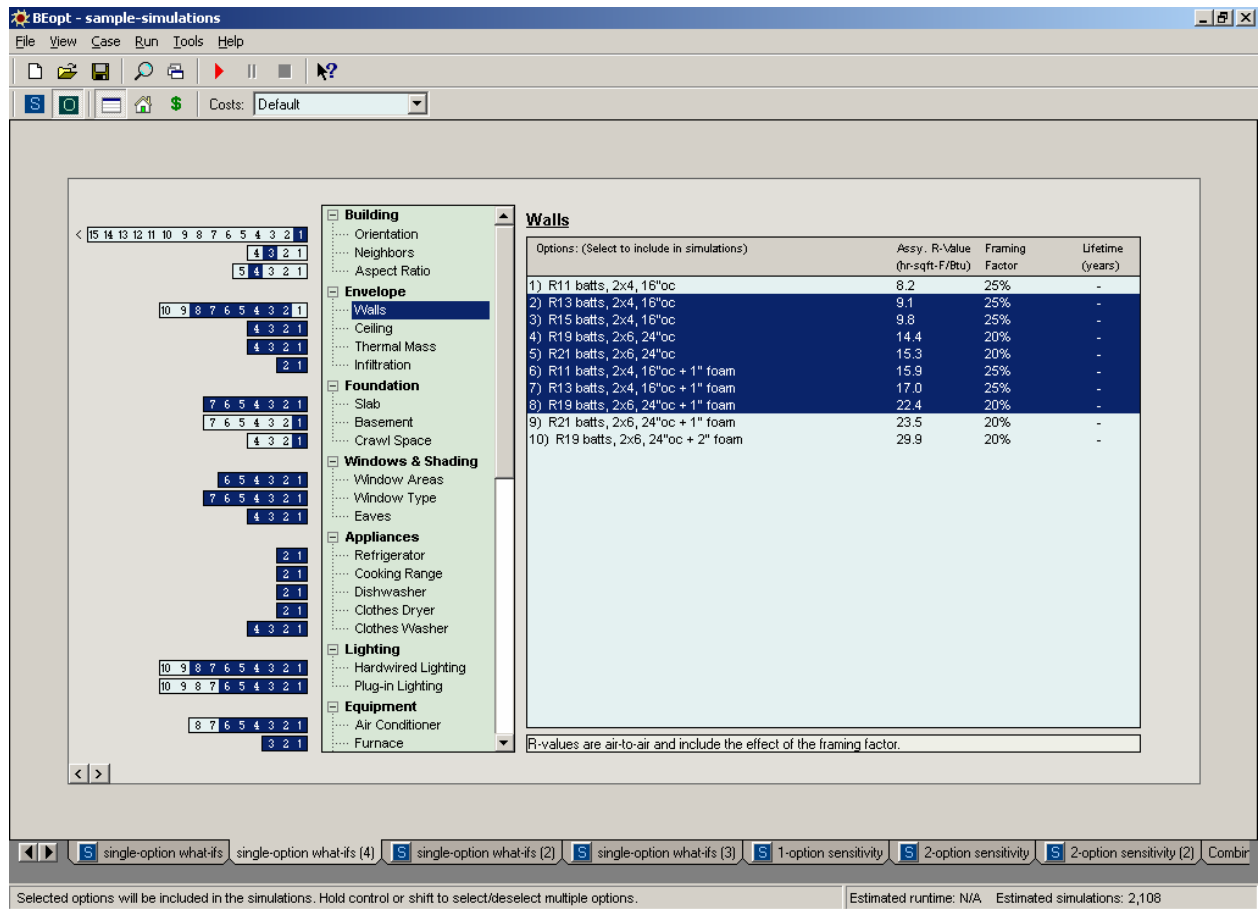

Fig. 8: Input options selection screen

in which these combinations are explicitly selected for the optimization. Likewise, the user can create Exclude Combinations categories such that certain combinations are explicitly excluded from the optimization – usually as a way of reducing runtime for combinations that the user knows are not cost-effective.

With the options selected, the BEopt software can run an optimization of the possible combinations of options. For selected options similar to those in Figure 5, optimization would involve approximately 1000 simulations and approximately 1.5 hours of computer run-time.

7. Output Screen (Results Browser)

Once an optimization process has been run,

the output screen can be displayed. Figure 9 illustrates a typical example of the output screen. For each case, the BEopt output screen displays the results in three different graphs: the path to zero net energy graph located in the upper left corner of the screen, the end-use graph in the bottom left corner, and the option costs graph on the right side of the screen.

7.1 Main Output Screen

The upper left graph in Figure 9 shows optimal and near optimal points along the path to zero net energy. The x-axis displays the percent of energy saved compared to the base case, whereas the y-axis shows annual energy-related costs. Energy savings are calculated relative to a reference: either a user-defined base-case building or a climate-
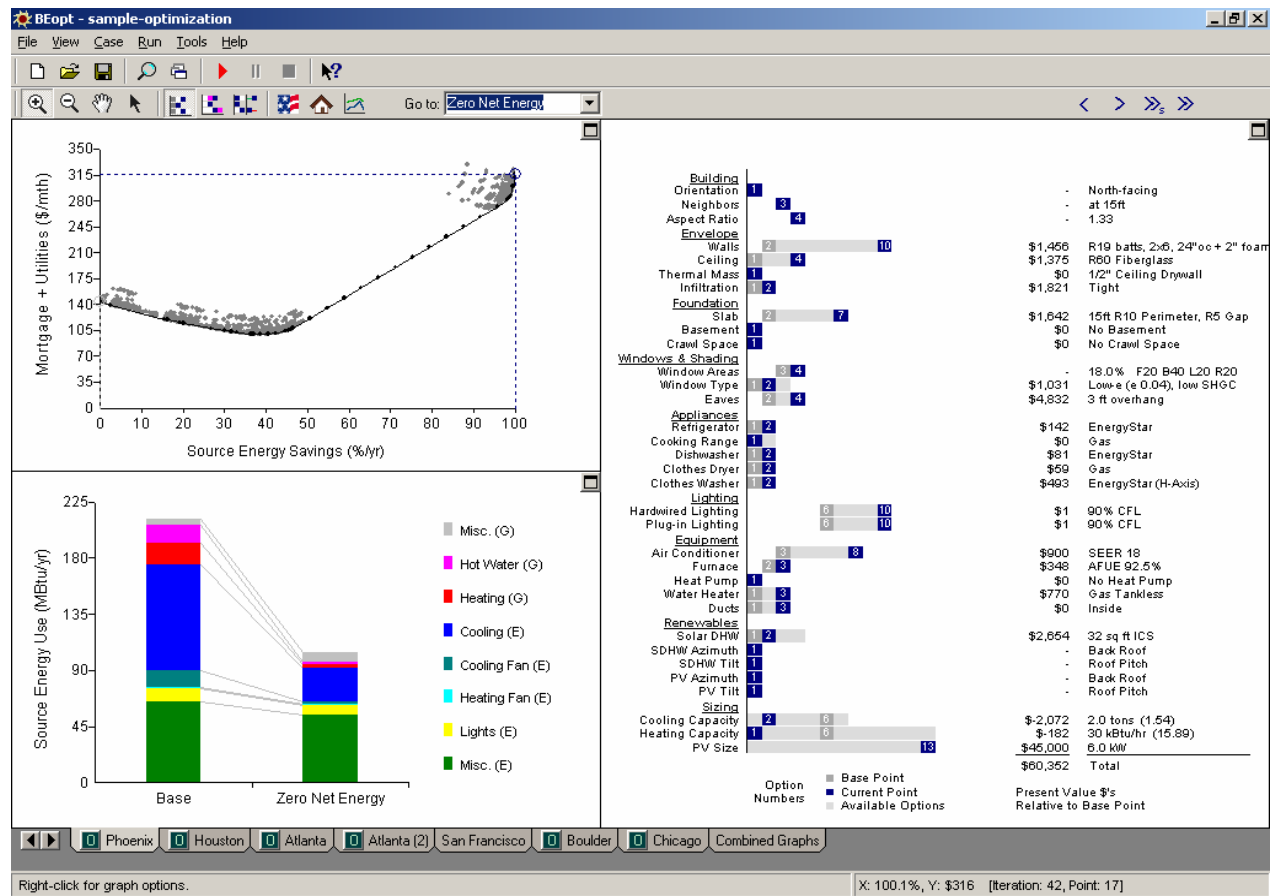

Fig. 9: Output screen for single optimization case (Phoenix)

specific Building America Benchmark building automatically generated by the BEopt software. Energy-related costs include utility bills, the cost of efficiency measures included in the mortgage payment, and the present value of future replacement costs for options with lifetimes less than the analysis period, typically 30 years. Each marker represents a particular simulated building design. The curve connects the points with the lowest annualized energy cost for any given energy savings. For any selected point (or points), the BEopt software will display associated results in the End Use Breakdown and Options graphs. The user can quickly navigate to optimal points at specified energy savings. The user can also zoom in and select any point (or points) on the graph. The sequence through which the BEopt software determined the optimal points during the optimization can be followed one iteration at

a time or replayed entirely by clicking the "step" and "play" buttons on the results toolbar.

The lower left graph in Figure 9 shows end-use values (gas miscellaneous, gas hot water, gas heating, electric cooling, etc.) as colored stacked bars. The left-hand bar shows results for the base case; the right-hand bar shows results for the selected point. The user can select whether the y-axis shows building energy consumption in terms of source energy (MBtu/year), site energy (MBtu/year), or cost of energy ($/year) and whether the current point results are relative to the Building America benchmark (or base case) or the previous point. If multiple points are selected in the upper left graph, the corresponding results are shown here.

The right-hand graph in Figure 9 displays option data for a selected point or points. The range of possible options is shown in
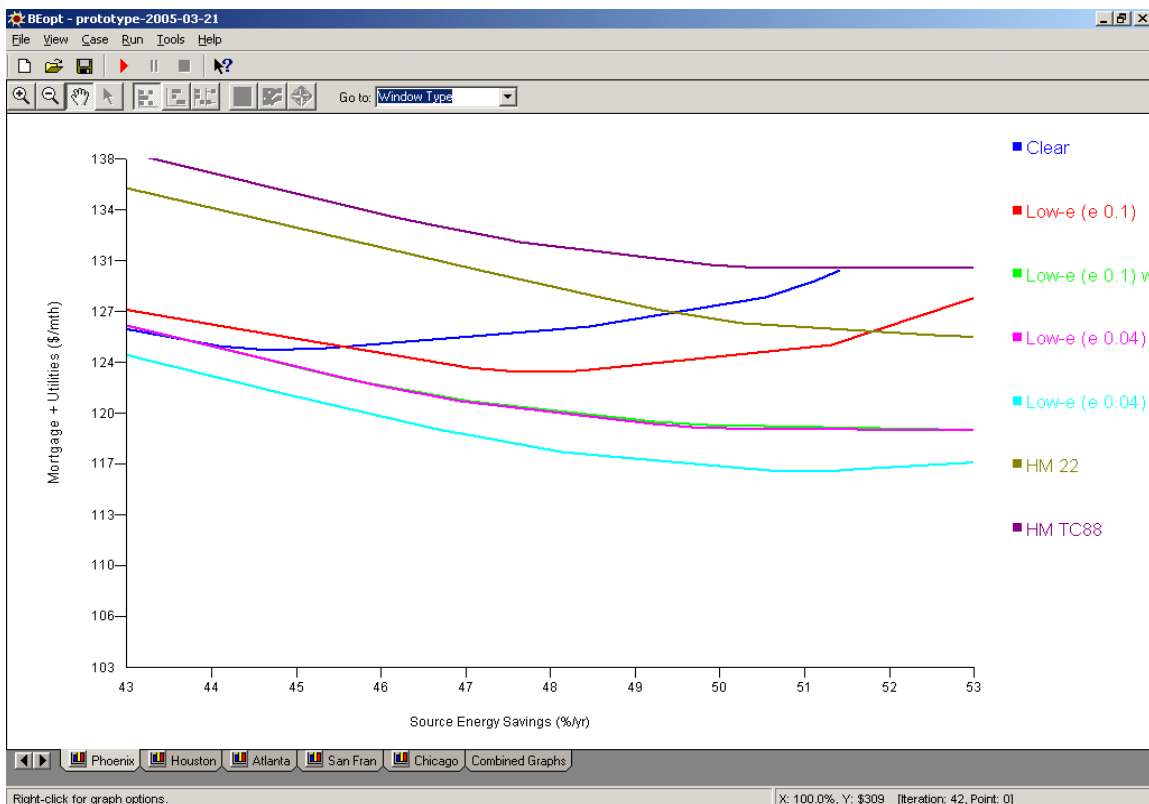

Fig. 10: Options sensitivity graph

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light grey. For the currently selected point (50% source-energy savings in this example), options are shown in dark blue, and the options for the previous point (40% source-energy savings) are shown in magenta. Option names are shown to the right, and option costs are shown relative to the base case and totaled at the bottom of the column. If multiple points are selected in the upper left graph, the corresponding results are shown here.

7.2 Option Sensitivity Graphs

As another alternative to the upper left graph, option sensitivity graphs are available for each category (see Figure 10 for window type, for example). For each option, a curve shows the lower boundary of cash flow values for all building designs incorporating that option, based on all simulation results from the optimization. This type of graph shows the range of energy savings over which certain options are optimal and how far other options are from being competitive at a given level of energy saving.

7.3 Detailed Output Displays

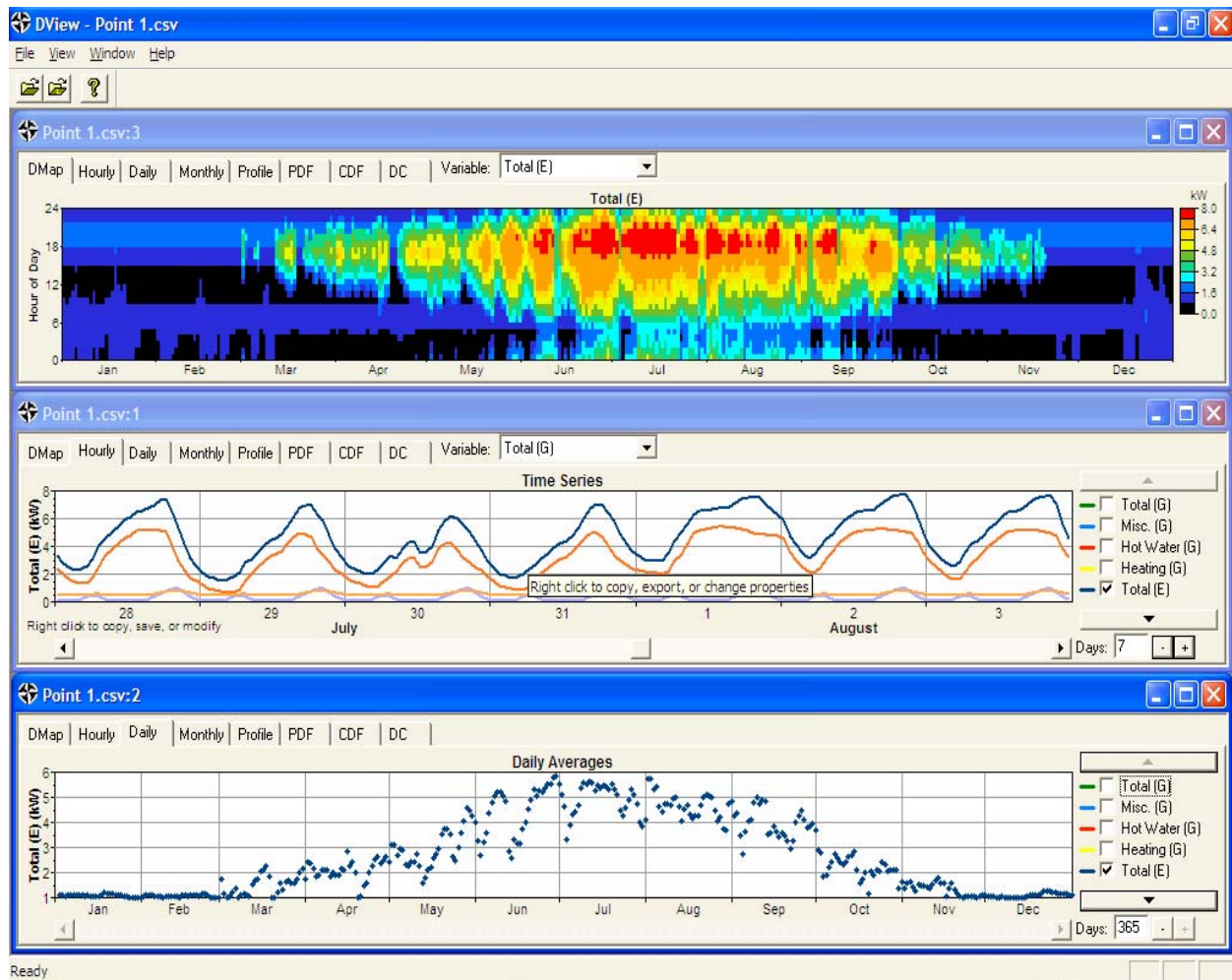For any simulation result, hourly results can be generated and various detailed outputs displayed (Figure 11).

Fig. 11: Sample of detailed output displays

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7.4 Combined Graphs

When two or more cases contain output, a tab appears to the right of all other case tabs. This tab displays an output screen (Figure 12) with all cases, or a user-selected subset of cases, compared on the same three graphs previously described.

The path-to-zero-net-energy curves are overlaid, and the end-use graph compares results for zero-net-energy designs for each case. The right-hand graph shows comparative options data for all cases. For the base case, option data are shown in a non-combined graph. For other cases, options are only shown if they are different than in the base case; indicators (red and green bars) show the direction and

magnitude of the differences. To make the comparative options graph as concise as possible, the BEopt software automatically selects the case with the fewest differences with other cases to be the base case and then orders the other cases beginning with those with the fewest differences

8. Summary

The BEopt computer program uses simulation and optimization to find optimal and near-optimal building designs along the path to zero net energy. To facilitate effective use of optimization, the BEopt user interface includes the following features:

- A main input screen that allows the user to select, from many predefined options,
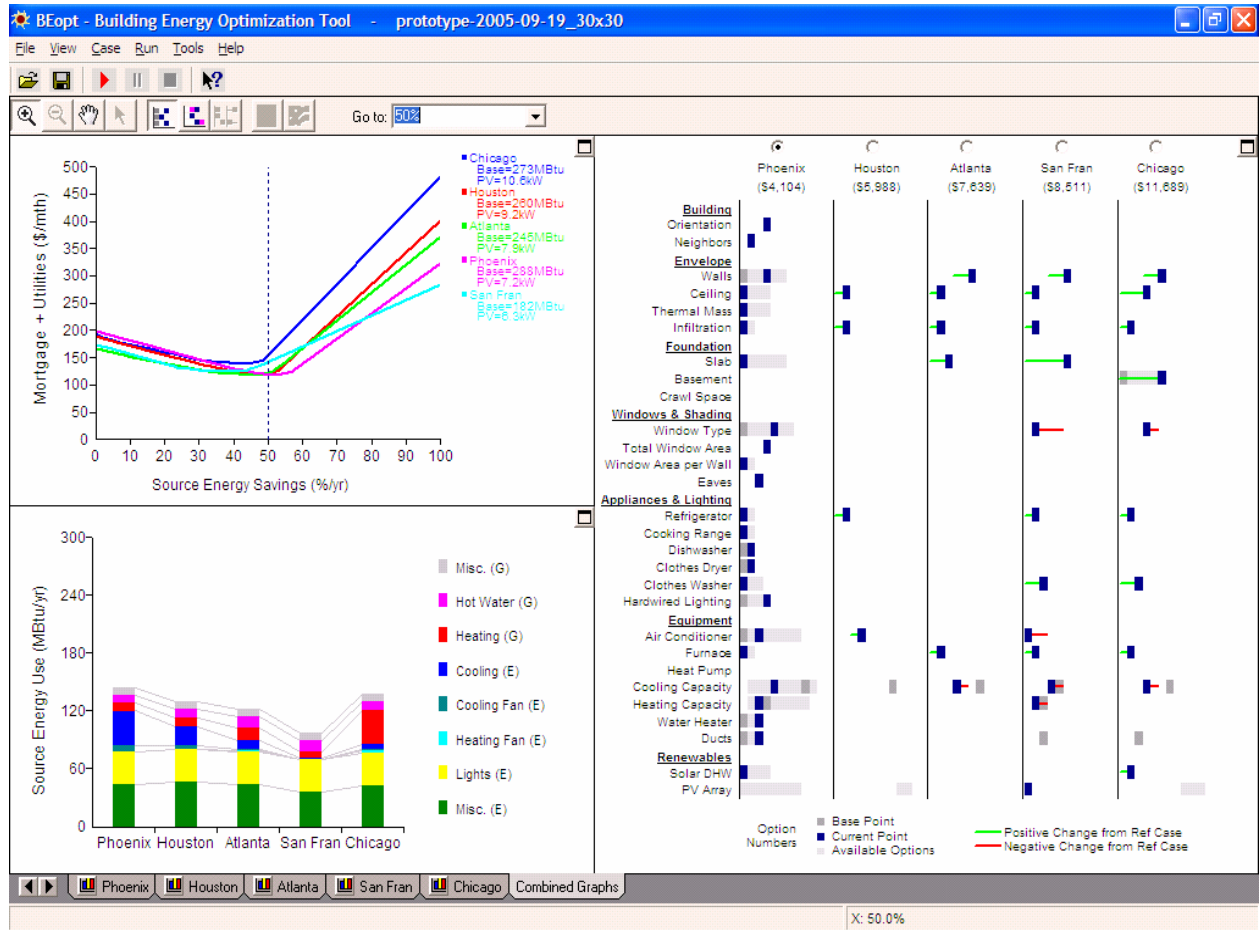

Fig. 12: Output screen for multiple cases

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those to be used in the optimization

- An output screen that allows the user to display detailed results for many optimal and near-optimal building designs
- An options library spreadsheet that allows a user to review and modify detailed information on all available options
- Energy savings that are calculated relative to a reference: either a user-defined base-case building or a climate-specific Building America Benchmark building
- Multiple cases that allow analysis of different climates, economic parameters, PV system characteristics, or the options selected for optimization
- Combined graphs that allow comparison of results from multiple cases.

9. Acknowledgments

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13. SUPPLEMENTARY NOTES

14. ABSTRACT *(Maximum 200 Words)*
BEopt is a computer program designed to find optimal building designs along the path to ZNE. A user selects from predefined options in various categories to specify options to be considered in the optimization. Energy savings are calculated relative to a reference. The reference can be either a user-defined base-case building or a climate-specific Building America Benchmark building automatically generated by BEopt. The user can also review and modify detailed information on all available options in a linked options library spreadsheet. BEopt calls the DOE2 and TRNSYS simulation engines and uses a sequential search technique to automate the process of identifying optimal building designs along the path to ZNE. BEopt finds these optimal and near-optimal designs based on discrete building options reflecting realistic construction options. BEopt handles special situations with positive or negative interactions between options in different categories. The BEopt software includes a results browser that allows the user to navigate among different design points and retrieve detailed results regarding energy end-use and option costs in different categories. Multiple cases, based on a selected parameter such as climate, can be included in a BEopt project file for comparative purposes.

15. SUBJECT TERMS
Building America; U.S. Department of Energy; BEopt; building energy simulation software; building energy optimization; building energy use modeling

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