

BEopt: Software for Identifying Optimal Building Designs on the Path to Zero Net Energy

Preprint

Craig Christensen
National Renewable Energy Laboratory

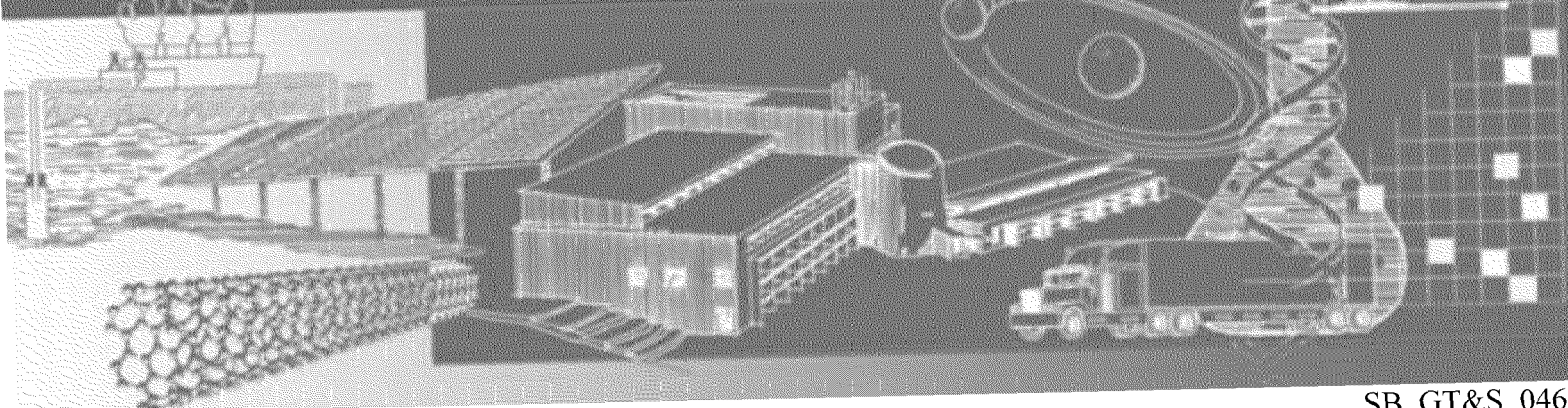
Scott Horowitz, Todd Givler, Adam Courtney
University of Colorado

Greg Barker
Mountain Energy Partnership

*To be presented at ISES 2005 Solar World Congress
Orlando, Florida
August 6–12, 2005*

Conference Paper
NREL/CP-550-37733
April 2005

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



NOTICE

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

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

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

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

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

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

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



Printed on paper containing at least 50% wastepaper, including 20% postconsumer waste

BEOPT: SOFTWARE FOR IDENTIFYING OPTIMAL BUILDING DESIGNS ON THE PATH TO ZERO NET ENERGY

Craig Christensen
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401
craig_christensen@nrel.gov

Scott Horowitz, Todd Givler,
Adam Courtney
University of Colorado
428 UCB, ECOT 441
Boulder, CO 80309

Greg Barker
Mountain Energy Partnership
13900 North 87th St.
Longmont CO 80503
gbarker123@aol.com

ABSTRACT

A zero net energy (ZNE) building produces as much energy on-site 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 owning and operating costs.

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 optimal and near-optimal designs along the path 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.

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 on-site as it uses annually.

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. 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.)

2. THE PATH TO ZERO NET ENERGY

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 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

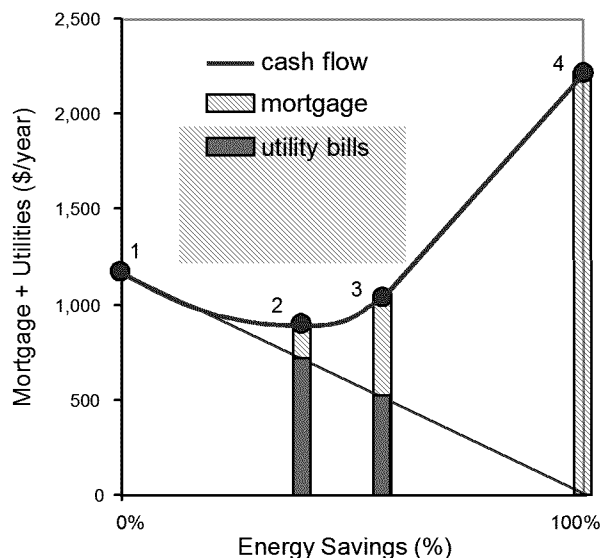


Fig. 1: Conceptual plot of the path to ZNE.

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 are shown in Figure 1 and 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.

3. BEOPT SOFTWARE

BEopt is a computer program designed to find optimal building designs along the path to ZNE. In addition to an optimization search, BEopt 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 (1) in a linked options library spreadsheet.

BEopt calls the DOE2 (2) and TRNSYS (3) simulation engines and automates the process of identifying optimal building designs along the path to ZNE using a sequential search technique (4). At each step along the path, BEopt runs individual simulations for all user-selected options and searches for the most cost-effective combination of options.

The BEopt 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, reflecting realistic construction options. Third, multiple near-optimal designs are identified at each particular energy savings level, providing design alternatives.

BEopt 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 BEopt (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.

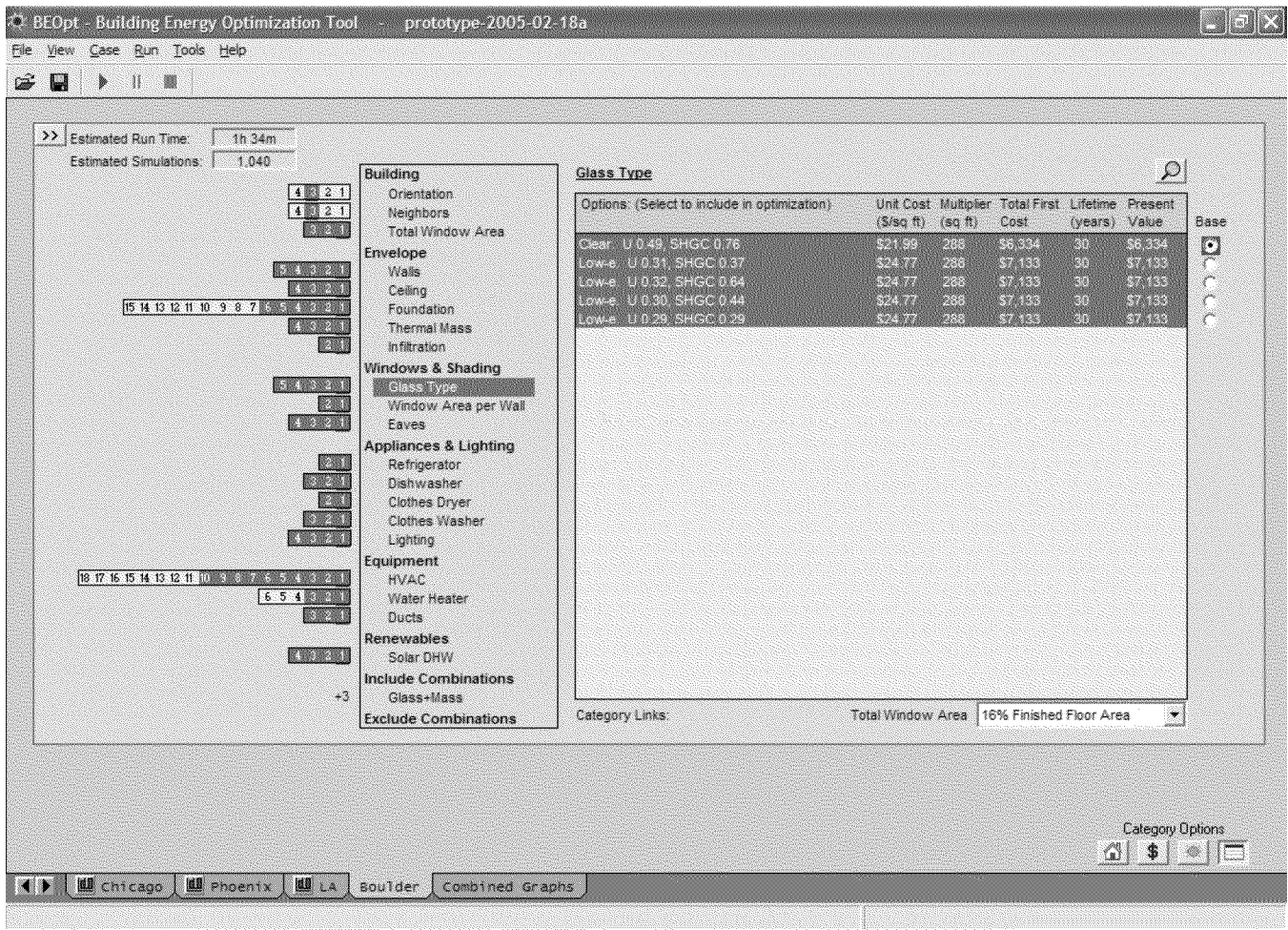


Fig. 2: BEOpt main input screen.

4. INPUT SCREEN (OPTION SELECTION)

Upon opening a project file, BEOpt scans the options library spreadsheet and loads categories and options associated with the project (Figure 2).

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

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 BEOpt to consider during optimization.

In other situations, subsets of options may be mutually exclusive. In the Foundation category, for example, options exist for slab 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 or not 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).

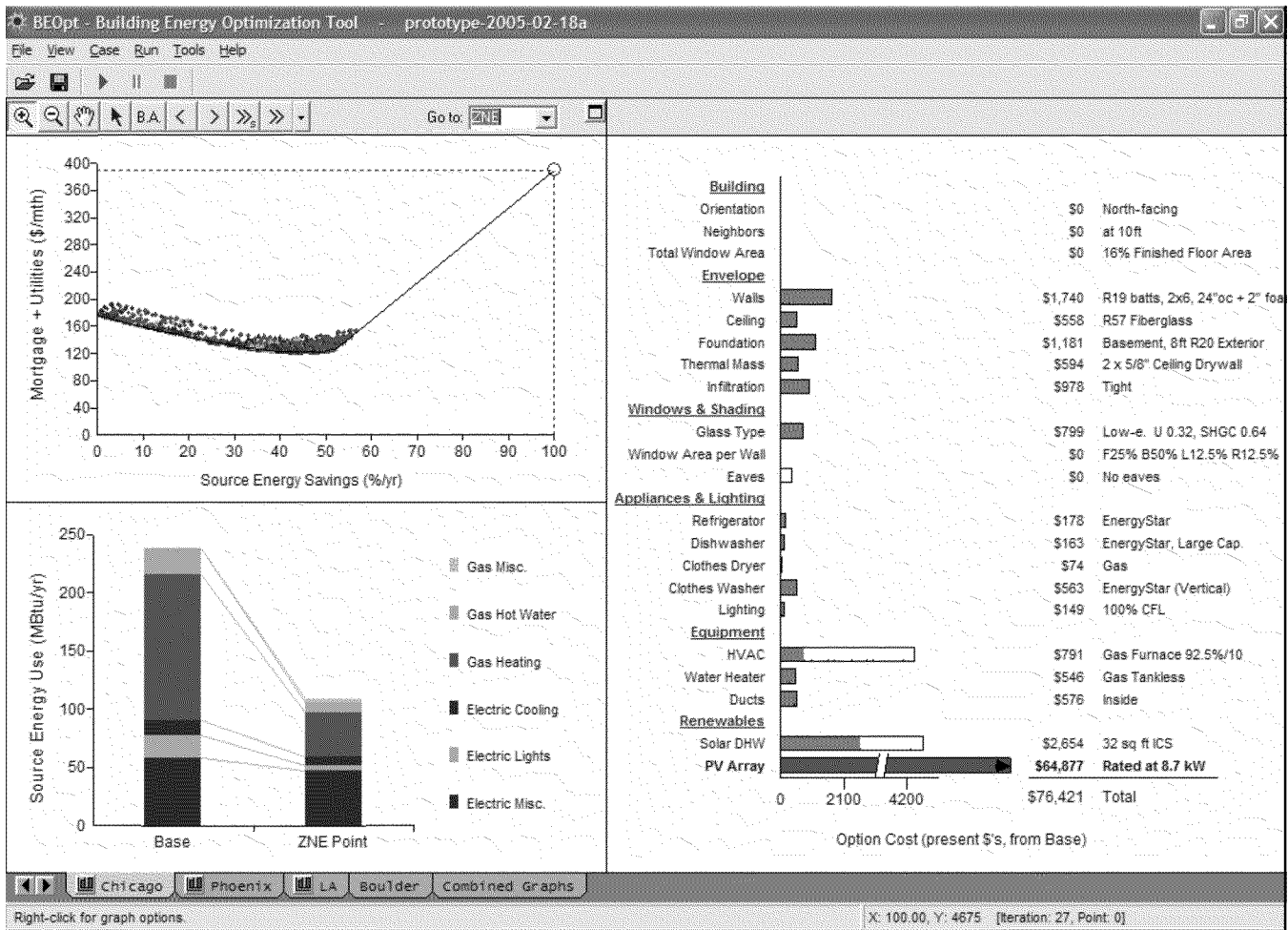


Fig. 3: BEOpt output screen.

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 BEOpt. However, if the user has the technical experience to recognize this situation, an Include Combinations category (Figure 2, “Glass+Mass”) can be created 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, BEOpt can run an optimization of the possible combinations of options. For selected options similar to those in Figure 2, optimization would involve approximately 1000 simulations and approximately 1.5 hours of computer run-time.

5. OUTPUT SCREEN (RESULTS BROWSER)

Once an optimization process has been run, the output screen can be displayed. Figure 3 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.

Microsoft Excel - BEoptOptions_022405_TG-conf paper only.xls

File Edit View Insert Format Tools Data Window Help

SnagIt Window

A600 = Glass Type

Glass Type		Key: Calculated Value Linked to Summary					
General							
Option Number		BA Benchmark	1	2	3	4	5
BEOpt Option Name			Clear, U 0.49, SHGC 0.76	Low-e, U 0.32, SHGC 0.64	Low-e, U 0.30, SHGC 0.44	Low-e, U 0.31, SHGC 0.37	Low-e, U 0.29, SHGC 0.29
Glass-Type-Code (From the DOE2 Glazing Library)			2001	2641	2661	2637	2667
All windows are double glazed with air between the panes.							
Energy							
U-value	Btu/sqft-hr-F	0.527	0.49	0.32	0.30	0.31	0.29
SHGC		0.652	0.76	0.64	0.44	0.37	0.29
Economics							
First Cost	\$/window		\$24.00	\$24.00	\$24.00	\$24.00	\$24.00
Cost / Unit	\$/sqft		\$21.99	\$24.77	\$24.77	\$24.77	\$24.77
Option First Cost			See Note Below	See Note Below	See Note Below	See Note Below	See Note Below
Life	years		30	30	30	30	30
Source			Kitzman's	Assumption	Assumption	Kitzman's	Assumption
Prices are for Hurd 3048 double-hung, vinyl frame windows.							
Kitzman's is in Rockford, IL. (815) 965 6885. Prices quoted 10/22/02.							
The cost / unit is the cost per square foot of the entire window assembly (glazing and frame). Total window cost is a function of total window area. Total window cost is determined by BEOpt for each combination of total window area and glass type.							
Constants							
Window Type			Hurd 3048 Double Hung, Vinyl Frame				
Width	in		29.50				
Height	in		47.50				
Area	sq ft		1,377				
Units			sq ft				
Units Needed			This is a function of Total Window Area				
Benchmark							
HDD	degF*days		1050				
U_window	Btu/(hr*sqft*degF)		0.79				
SHGC			0.65				
R_outside air	(hr*sqft*degF)/Btu		0.190				
R_inside air	(hr*sqft*degF)/Btu		0.680				
U_glass	Btu/(hr*sqft*degF)		0.923				
SHGC_glass			0.933				
U_window and SHGC include the framing and sash.							
Framing Factor			0.22				
U_frame	Btu/(hr*sqft*degF)		0.319				
SHGC_frame			0				

DETAILS / SUMMARY / INPUT FILES / T_mains / Weather / Geometry / BM Interface / PV / LOG

Go to: Glass Type

Ready

Fig. 4: BEopt options library spreadsheet.

5.1 Path to Zero Net Energy Graph

This graph details the 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 while 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-specific Building America Benchmark building automatically generated by BEopt. 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 colored marker represents a particular simulated building design. Points shown in the same color and symbol shape are combinations that were simulated during a particular optimization iteration. (Therefore, the number of colors matches the number of iterations performed by BEopt.) The curve connects the points with the lowest annualized energy cost for any given energy savings.

For any selected point, BEopt will display associated results in the End Use Breakdown and Options Costs graphs. The user can quickly navigate to optimal points at specified energy savings. The user can also zoom in and select any (non-optimal) point on the graph. The sequence through which BEopt 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.

5.2 End Use Graph

End use values (gas misc., gas hot water, gas heating, electric cooling, etc.) are shown 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).

5.3 Options Cost Graph

The options cost graph displays data by category with bar outlines indicating the maximum possible option cost within the set of selected options. For a selected point, the shaded bars and values indicate option costs. Option names are shown to the right. Option costs shown are relative to the base case and totaled at the bottom of the column.

When two or more cases contain output, a Combined Graphs tab appears to the right of all other case tabs. This tab displays an output screen (there is no associated input screen) with all cases compared on the same three graphs previously described. The path-to-zero-net-energy curves are overlaid, while the option cost graph and the end use graph compare results for zero net energy designs for each case.

6. OPTIONS LIBRARY

The options library spreadsheet (Figure 4) contains detailed information for all the BEopt categories and options. While some users may only use the BEopt input screens to specify optimization inputs, 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). 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.

7. CONCLUSIONS

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:

The main input screen that allows the user to select from many predefined options, those to be used in the optimization,

The output screen that allows the user to display detailed results for many optimal and near-optimal building designs,

The options library spreadsheet that allows a user to review and modify detailed information on all available options,

Energy savings 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, and

Combined graphs that allow comparison of results from multiple cases.

8. ACKNOWLEDGMENTS

This work was supported by the U.S. Department of Energy, Office of Building Technologies. The support of Ed Pollock and George James, Building America, and Lew Pratsch, Zero Energy Buildings, is gratefully acknowledged. We also thank Ren Anderson, and Ron Judkoff of NREL’s Center for Buildings and Thermal Systems, along with Ed Hancock and Paul Reeves for their valuable discussions, and contributions on the topic of this paper.

9. REFERENCES

- (1) Hendron, R., Building America Research Benchmark Definition, NREL/TP-550-37529, National Renewable Energy Laboratory, February 2005
- (2) York, D. and Capiello, C., eds., 1981, DOE-2 Reference Manual (Version 2.1A), Lawrence Berkeley National Laboratory, Berkeley, CA
- (3) Klein, S., et al, 1996, TRNSYS: A Transient System Simulation Program – Reference Manual, Solar Energy Laboratory, University of Wisconsin, Madison, WI
- (4) Christensen, C., Barker, G., Horowitz, S., A Sequential Search Technique for Identifying Optimal Building Designs on the Path to Zero Net Energy, Proceedings of the Solar 2004, Portland, OR, American Solar Energy Society, 2004

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

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

PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ORGANIZATION.

1. REPORT DATE (DD-MM-YYYY) April 2005			2. REPORT TYPE Conference Paper		3. DATES COVERED (From - To) August 6 – 12, 2005	
4. TITLE AND SUBTITLE BEopt: Software for Identifying Optimal Building Designs on the Path to Zero Net Energy; Preprint				5a. CONTRACT NUMBER DE-AC36-99-GO10337		
				5b. GRANT NUMBER		
				5c. PROGRAM ELEMENT NUMBER		
6. AUTHOR(S) C. Christensen, S. Horowitz, T. Givler, A. Courtney, and G. Barker				5d. PROJECT NUMBER NREL/CP-550-37733		
				5e. TASK NUMBER BET5.8001		
				5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401-3393				8. PERFORMING ORGANIZATION REPORT NUMBER NREL/CP-550-37733		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S) NREL		
				11. SPONSORING/MONITORING AGENCY REPORT NUMBER		
12. DISTRIBUTION AVAILABILITY STATEMENT National Technical Information Service U.S. Department of Commerce 5285 Port Royal Road Springfield, VA 22161						
13. SUPPLEMENTARY NOTES						
14. ABSTRACT (Maximum 200 Words) A zero net energy (ZNE) building produces as much energy on-site 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 owning and operating costs. BEopt is a computer program designed to find optimal building designs along the path to ZNE. A user selects from among 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 and the Building America Benchmark in a linked options library spreadsheet.						
15. SUBJECT TERMS zero net energy building; net-metered PV system; active solar; ZNE; energy-related house costs; energy-efficient housing; Beopt						
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UL	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON	
a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified			19b. TELEPHONE NUMBER (Include area code)	

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18