Using
BEopt
to Optimize
Home Energy
Performance

by Eric Wilson

The story of BEopt starts in October 2000, when a seminal two-day workshop was held at the National Renewable Energy Laboratory (NREL) to explore the then-novel concept of zero net energy (ZNE) buildings. Representatives from the home-building industry, solar-thermal and PV manufacturers, consultants, national labs, and U.S. Department of Energy (DOE) came together to discuss what would be necessary for the broad adoption of ZNE buildings. One conclusion was that we needed a tool to determine the most cost-effective combination of technologies for ZNE homes. In other words, we needed to figure out how much efficiency to bundle with solar. More than a decade later, the economics have changed: Solar PV costs half what it did then. But the question remains the same and can be heard echoing in discussions about "how much insulation is too much?"

In response to the need for such a tool, NREL developed BEopt (short for Building Energy Optimization), with funding from DOE and a number of key partners, including the California Public Utilities Commission, the California Energy Commission, and the Bonneville Power Administration. Like other energy-modeling tools, BEopt can evaluate individual building designs. But BEopt's optimization capability makes it unique. The optimization search technique can quickly identify the most cost-effective combinations of efficiency measures and solar-energy systems along the path to ZNE without having to evaluate every possible combination of measures. Whether you're interested in achieving 50% savings, going all the way to ZNE or beyond, or just finding the least expensive solution, BEopt can help you get there (see "The BEopt Optimization Curve" on p. 28).

By 2005, research teams in DOE's Building America program were using BEopt to optimize the designs of their partner production home builders. Since then, these Building America partners have built over 55,000 homes, incorporating many of the design strategies developed using BEopt optimizations. These design optimizations have likely impacted many more homes through their influence on the Energy Star Certified New Homes program and energy codes.
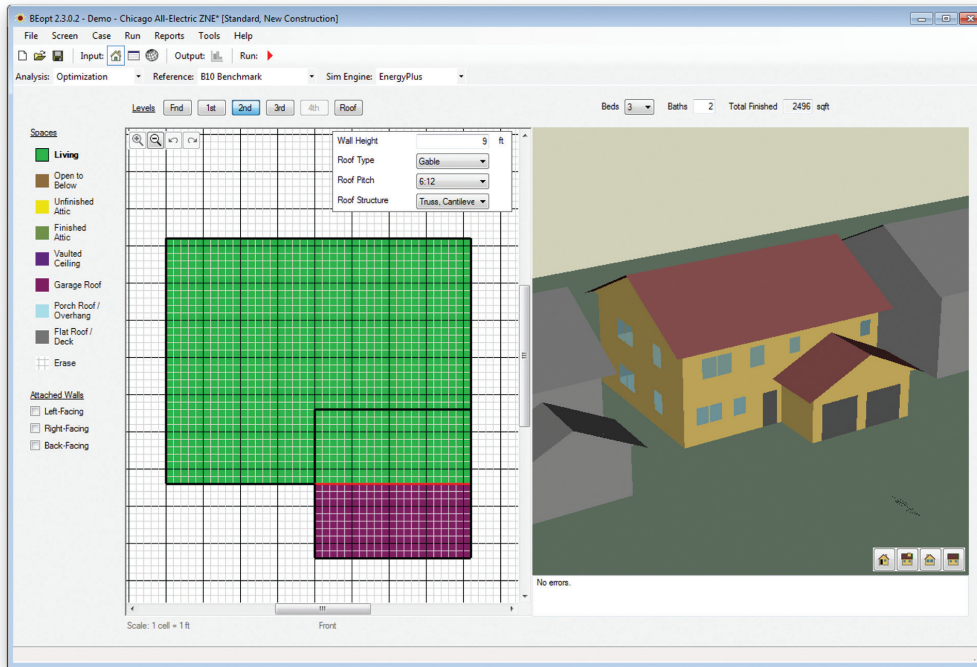
Geometry Input Screen

Figure 1. The Geometry Input Screen has a 2D drawing tool for quick input of building geometry, and an instant 3D rendering to verify correctness.

The first publicly available version of BEopt was released in November 2010. Until then, BEopt was available to Building America research partners only. Its use has since expanded to utilities, state government organizations, manufacturers, architecture and engineering firms, nonprofits, and universities, as well as home build-

ers outside the Building America program. BEopt has also been used for DOE initiatives on rebuilding in New Orleans after Hurricane Katrina, and after the massive 2007 tornado in Greensburg, Kansas.

Simultaneously Powerful and Easy to Use

Our team at NREL has sought to make BEopt powerful and easy to use; anyone with a basic understanding of buildings and energy should find it user-friendly. BEopt is a plug-and-play interface that uses EnergyPlus, DOE's state-of-the-art whole-building simulation engine to run hourly or subhourly simulations behind the scenes.

BEopt has three input screens. Figure 1 shows the Geometry Input Screen, where the shape and size of the building is defined. The building's components (wall insulation, air leakage, air conditioner efficiency, and so on) are selected on the Options Screen. Users can select from built-in options or define their own custom options. In Design mode, one option per category is selected.
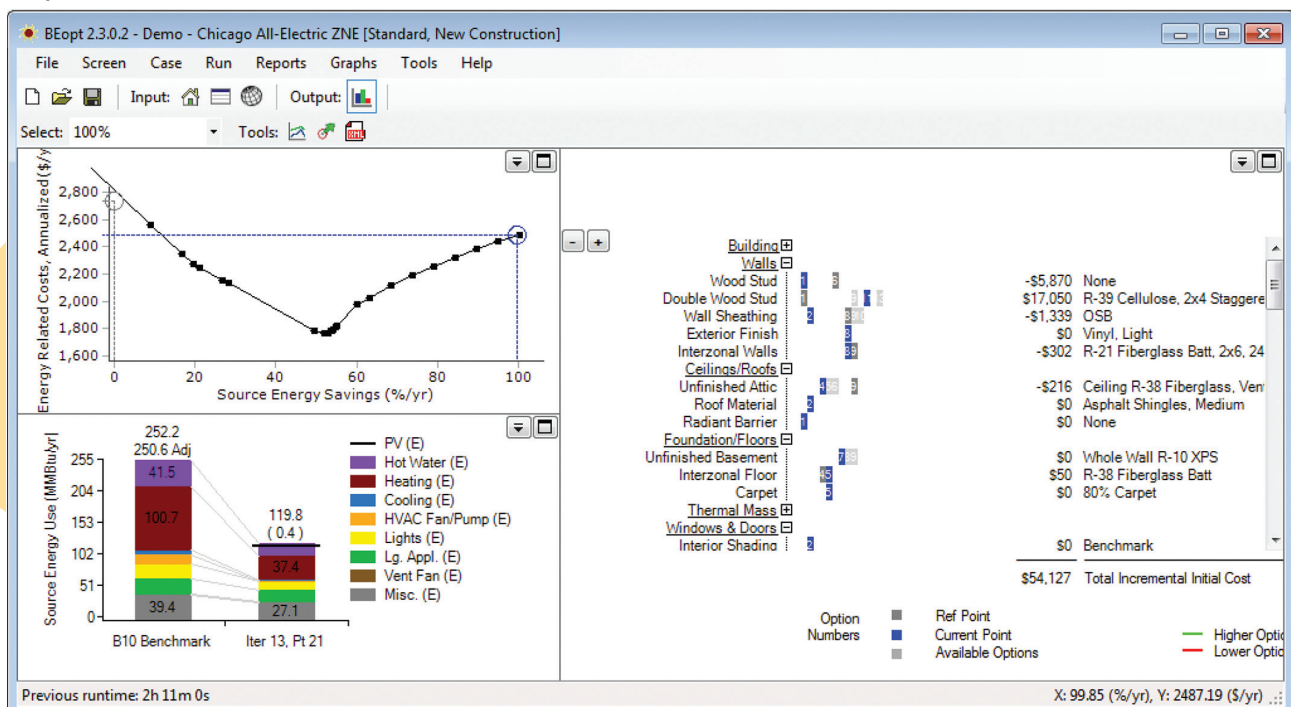
Output Screen

Figure 2. The Output Screen displays the optimization curve *(upper left)*. Each point represents a different design and can be selected to examine the breakdown of energy end uses *(bottom left)* and the descriptions and costs of the options making up that design *(right side of screen)*.

In Parametric and Optimization modes, multiple options per category can be selected. The Site Screen is used to choose the weather location, specify utility rates, and make any changes to economic assumptions.

Figure 2 shows the Output Screen, where the results of the simulations or optimization are displayed. The optimization curve is plotted in the upper left graph. Each point represents a different design and can be selected to examine in detail. The breakdown of energy end uses for the selected design(s) is shown in the bottom left graph. The descriptions and costs of the options making up those designs are shown on the right-hand side of the screen.

Public Data Sources Enrich BEopt Capabilities

BEopt uses a number of public data sources to make modeling even easier. The National Residential Efficiency Measures Database is a publicly available, centralized resource of residential building retrofit measures and costs for the U.S. building industry. The database provides default costs and lifetimes for all measures included in BEopt. Users should always use actual quoted costs when available, but this database of default cost assumptions is very helpful when actual costs are not available.

Another public data source that BEopt uses is the U.S. Utility Rate Database, which provides free rate structure information from nearly 3,500 utility companies across the United States. Thousands of residential rates are made available in BEopt and are searchable by ZIP code. Why does this matter? Some utility rates are simple, with a flat energy charge ($/kWh) and a fixed monthly customer charge ($). However, many residential rates are less straightforward, with tiered or time-of-use structures. In *tiered* rates, the energy charge may be $0.10/kWh for the first 500 kWh used each month, $0.12/kWh for the next 500 kWh, and $0.15/kWh thereafter. In *time-of-use* rates, a higher energy charge is imposed during certain hours (for example, from 2 pm to 8 pm during the summer). Some rates have both tiered and time-of-use components.

These complex rate structures are important when evaluating efficiency measures and solar PV. BEopt automatically calculates the home's utility bills based on the selected rate structure, so the user doesn't have to do so. While the Utility Rate Database rates are generally updated within six months of changes, BEopt provides an interface so users can input their own custom utility rate structures, whether real or speculative.

For homes with net-metered PV, BEopt can account for situations where annual excess generation is sold back to the utility at a lower rate than the retail rate. BEopt can also model situations where electricity generated on-site is sold directly to

the grid at a given rate (gross feed-in tariff) instead of offsetting on-site consumption.

Standard or Customized Occupant Behavior

By default, BEopt uses a standard set of assumptions about occupant behavior, including thermostat set points, number of occupants, hot-water usage, appliance usage, other plug loads, and schedules. These are defined in the "2014 Building America House Simulation Protocols" (HSP), which provide standard operating assumptions for the Building America program. Standard operating conditions are important when performing *asset* evaluations—that is, when comparing one home to another, independent of occupants. On the other hand, BEopt users may change these assumptions to reflect actual current occupants. For example, the HSP uses 76°F for the cooling set point, but if the current occupants are known to use a cooling set point of 80°F, this can be changed for the BEopt analysis. Similar changes can be made to hot-water usage, appliance usage, and plug loads based on measured data or to match utility bills.

Case Studies

As I mentioned earlier, BEopt has been used extensively by Building America teams working with production home builders. Here are some other examples of how BEopt has been used.

NREL/Habitat for Humanity ZNE Home

This collaboration between NREL and Habitat for Humanity of Metro Denver was an early example of BEopt being used to optimize the design of a ZNE home. (See "The Little House That Could," *HE* Nov/Dec '06, p. 24.) The 1,200 ft², three-bedroom home in Wheat Ridge, Colorado, was completed in 2005. BEopt was used to find the most affordable combination of insulation, efficient equipment, and passive- and active-solar features to reach the ZNE goal. The home features a superinsulated thermal enclosure (R-60 ceiling, R-40 double-stud walls, R-30 floor), low-e windows with

well-designed orientation and shading, a ductless gas heater supplemented with electric baseboard heaters, an energy recovery ventilator, solar water heating, and a 4kW PV system.

Design of a ZNE Low-Income Housing Development

In 2009, the Boulder County Housing Authority partnered with All American Group, HB&A Architects, Farnsworth Group engineers, and NREL to design and construct a pilot project of two buildings. BEopt was used to optimize the design of a one-story single-family

BEopt was used to find the most affordable combination of insulation, efficient equipment, and passive and active solar to reach the ZNE goal. The south-facing windows are well shaded by the roof overhang.

house and a two-story duplex. Before adding solar PV, the optimized designs achieved 37–42% source energy savings compared to the baseline designs, and had lower energy-related costs (mortgage payments plus utility bills) than the baseline. In other words, savings from the optimized design resulted in a positive cash flow to the homeowner from day 1 relative to the baseline design (before adding PV). The results of the pilot project were used to develop final design recommendations for the 153-unit ZNE infill development in Lafayette, Colorado.

Evaluating Missed Energy-Saving Opportunities
In 2014, the Partnership for Advanced Residential Retrofit Building America team published a report that evaluated data from 800 retrofits that were part of the Illinois Home

The BEopt Optimization Curve

BEopt's optimization mode is used to generate a curve showing the most cost-effective way to achieve energy savings along the path to ZNE. A simple explanation of the optimization curve is provided below. The percent energy savings is plotted on the horizontal axis (Figure A), and the annualized energy-related costs are plotted on the vertical axis. This annual cost consists of the utility bills each year plus the cost of energy efficiency measures that have been incorporated into mortgage or loan payments.
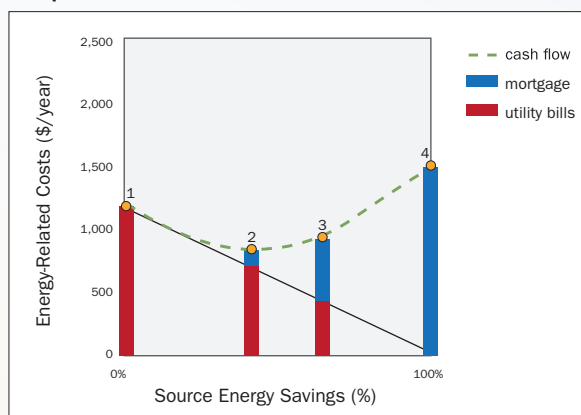
BEopt Curve

Figure A. The annual energy cost (cash flow) includes both the utility bills and the cost of energy efficiency measures that are included in mortgage or loan payments.

• Point 1: Reference Case
The reference case is the starting point for evaluating energy efficiency measures. For new construction, the reference case could be the Building America Benchmark (defined in the *2014 Building America House Simulation Protocols*) or it could be a user-defined reference case. For retrofits, the reference case is the existing building. The percent energy savings equals zero at this point. Also, the only energy-related costs are the monthly utility bills.

• • Point 2: Minimum Annual Cost
At each point along the path to ZNE, BEopt searches across all categories with selected options (wall type, ceiling type, window glass type, HVAC type, and so on) to identify the next-most cost-effective measure. Up to the minimum annual cost point, all the measures provide utility bill savings that exceed the additional mortgage or loan payment to cover the efficiency measure, so the path is downward sloping. Beyond the minimum-cost point, additional energy can be saved, but only with a net increase in annual costs. If the designer cares only about economics, he or she would stop at this minimum-cost point.

• • • Point 3: Solar PV Take-Off Point
Efficiency measures continue to be applied in order of cost-effectiveness. At some point, it becomes more expensive to save the next unit of energy with an energy efficiency measure than it is to produce that same unit of energy with on-site solar PV. Up to this point, all of the energy savings have come from building efficiency. From this point on, most of the energy savings result from on-site solar PV.

• • • • Point 4: Zero Net Energy
At the ZNE point, the building produces as much energy with PV as it consumes on an annual basis. In this simplified sketch, utility costs are zero. In reality, utility costs include fixed customer charges. If excess PV generation is needed to offset on-site gas use, the sell rate usually doesn't offset the cost of the gas use. BEopt includes detailed utility bill calculations, accounting for net metering rules and fixed or minimum charges. If the size of the PV system is limited by roof area, additional efficiency measures can be tacked on to reach the ZNE point.

Near-Optimal Designs
BEopt's iterative search technique will identify additional near-optimal designs. These designs provide equivalent solutions that may be more desirable based on builder or contractor preference.

Future Scenarios
Historically, the ZNE point has had total annual costs higher than the reference case. As the cost of solar PV falls, the slope of the PV part of the curve decreases. When the slope becomes negative, the ZNE point becomes the minimal cost point. BEopt users can change cost and economic assumptions to explore their effects on the optimization curve.

Performance program. Homeowner-selected retrofit packages were compared to the cost-optimal packages determined using BEopt. Two conclusions from the report are:

- The Illinois Home Performance retrofit packages focused on insulation and air-sealing measures, but missed out on potential cost-effective savings from space-heating and water-heating upgrades. The authors commented that program incentives could be revised to encourage measure packages that more closely match BEopt cost-optimal packages.
- Homes participating in a retrofit program could be grouped into archetypes based on year built, type of construction, number of stories, and so on. BEopt could be used to determine standardized retrofit measure packages for each of these archetypes. This would streamline the process of determining appropriate retrofit measure packages for each home, reducing program overhead costs, and maximizing both energy savings and cost-effectiveness.

Climate-Specific PH Building Standards

Another interesting use of BEopt has been to help inform the development of a new Passive House (PH) building standard for North America. See "PHIUS+ 2015 Climate-Specific Passive Building Standard: What's Changed, What Hasn't" on p. 32. The Passive House Institute US (PHIUS) partnered with Building Science Corporation to develop this standard. In a 2015 Building America report, they describe how the European PH standard was developed in the context of European climates and energy costs. The result was a standard roughly corresponding to economic optimum in that context. BEopt was used to study economic optimization for North American climates and energy costs. These optimizations formed the basis for the new standard drafted by the PHIUS Technical Committee.

A 153-unit ZNE infill development in Lafayette, Colorado.

HB&A ARCHITECTS

Looking Forward

As the home energy landscape continues to change, with even cheaper PV, new utility rate structures, and new technologies, BEopt will continue to be a useful tool for optimizing home energy performance. This summer, we will release a version of BEopt with expanded multifamily modeling capabilities. And in the coming years we'll be transitioning BEopt's residential analysis capabilities over to the OpenStudio platform, a cross-platform, open-source project that facilitates software development and community contributions. Register on the BEopt website to download BEopt and stay informed about these new developments. **H**ₑ

Eric Wilson *is an engineer in the Residential Buildings Research group at the National Renewable Energy Laboratory (NREL). His recent activities include developing multifamily modeling capabilities for the BEopt building energy optimization software, developing an analysis framework and data visualization for national residential building stock models, and leading updates of the Building America House Simulation Protocols.*

> For a step-by-step guide through the BEopt interface, go to "Getting Started with BEopt" in the online version of this article at homeenergy.org.

>> learn more

BEopt software is available for free download at http://beopt.nrel.gov.

The report on the two-day NREL workshop, *Next Steps on the Road to Zero Energy Buildings*, is available at http://infohouse.p2ric.org/ref /20/19462.pdf.

Training videos are available on the BEopt website at http://beopt.nrel .gov/trainingvideos. BEopt users can also use a support forum to ask questions and share their expertise; go to http://beopt.nrel.gov/forum.

To access the National Residential Efficiency Measures Database, go to http://www.nrel.gov/ap/retrofits.

To access the U.S. Utility Rate Database, go to http://en.openei.org /wiki/Utility_Rate_Database.

The 2014 Building America House Simulation Protocols can be downloaded from www.nrel.gov/docs/fy14osti/60988.pdf.

The NREL/Habitat for Humanity Zero Energy Home: A Cold Climate Case Study for Affordable Zero Energy Homes is available at www.nrel.gov /docs/fy08osti/43188.pdf.

For more details on the Lafayette project, including measured performance and lessons learned, see *Design and Evaluation of a Net Zero Energy Low-Income Residential Housing Development in Lafayette, Colorado*, at www.nrel.gov/docs/fy12osti/51450.pdf.

To download the 2014 report *Evaluation of Missed Energy Saving Opportunity Based on Illinois Home Performance Program Field Data: Homeowner Selected Upgrades vs. Cost-Optimized Solutions*, go to http://energy.gov/sites/prod/files/2014/07/f17/ba_case_study _illinois_home_perf.pdf.