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Searching for the Optimal Mix of Solar and Efficiency in Zero Net Energy Buildings

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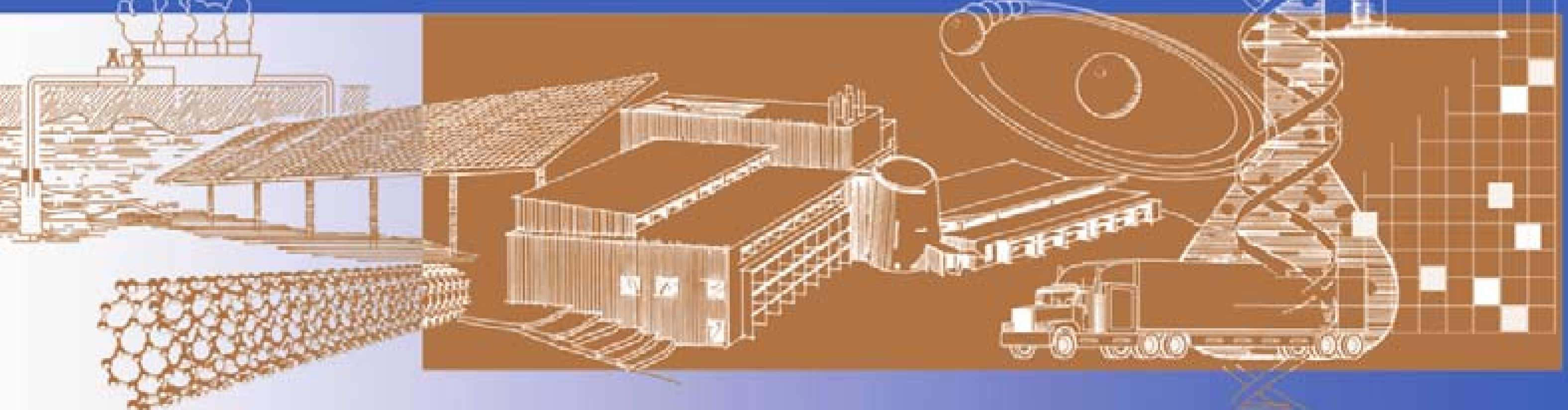

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SEARCHING FOR THE OPTIMAL MIX OF SOLAR AND EFFICIENCY IN ZERO NET ENERGY BUILDINGS

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ABSTRACT

Zero net energy (ZNE) buildings employ efficiency to reduce energy consumption and solar technologies to produce as much energy on site as is consumed on an annual basis. Such buildings leverage utility grids and net-metering agreements to reduce solar system costs and maintenance requirements relative to off-grid photovoltaic (PV)-powered buildings with batteries.

The BEopt software was developed to efficiently identify cost-optimal building designs using detailed hour-by-hour energy simulation programs to evaluate the user-selected options. A search technique identifies optimal and near-optimal building designs (based on energy-related costs) at various levels of energy savings along the path from a reference building to a ZNE design.

In this paper, we describe results based on use of the BEopt software to develop cost-optimal paths to ZNE for various climates. Comparing the different cases shows optimal building design characteristics, percent energy savings and cash flows at key points along the path, including the point at which investments shift from building improvements to purchasing PV, and PV array sizes required to achieve ZNE.

From optimizations using the BEopt software for a 2,000-ft^2 house in 4 climates, we conclude that, relative to a code-compliant (IECC 2006) reference house, the following are achievable: 1) minimum cost point: 22 to 38% source energy savings and 15 to 24% annual cash flow savings; 2) PV start point: 40 to 49% source energy savings at -10 to 12% annual cash flow savings; 3) break-even point: 43 to 53% source energy savings at 0% annual cash flow savings; and 4) ZNE point: 100% source energy savings with 4.5 to 8.1 kW_{DC} PV arrays and 76 to 169% increase in cash flow.

1. BACKGROUND

1.1. Types of Zero Energy Buildings

Off-grid photovoltaic (PV)-powered buildings are zero energy with regard to the electricity grid, but often use propane for space and water heating and to run a backup generator. However, the more recent concept of zero net energy (ZNE) buildings promises more widespread applicability in the U.S. housing sector. ZNE buildings use grid-tied, net-metered PV and active solar to produce as much energy as is used 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. For electricity purchased from a utility, source energy accounts for power plant generation efficiency and transmission and distribution losses, and source-to-site ratios are typically about 3, depending on the mix of electricity generation types (coal-fired, natural-gas combined-cycle, nuclear, hydropower, etc.) For purchased natural gas and propane, source-to-site energy ratios include production energy as well as transmission and distribution losses, and 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, as shown in Figure 1. The path to ZNE extends from a reference building (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

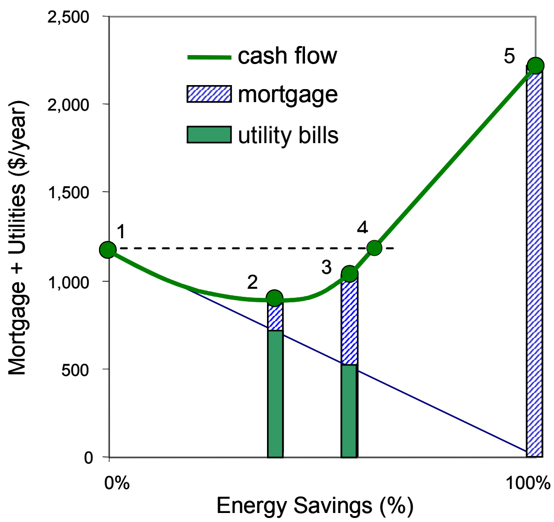

Fig. 1. Conceptual plot of the path to ZNE.

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 can be described as follows. From the reference building at point 1, energy use is reduced by employing building efficiency options (improvements in wall R-value, furnace annual fuel utilization efficiency [AFUE], air conditioner seasonal energy efficiency ratio [SEER], etc.). A minimum annual cost optimum occurs at point 2 (assuming the minimum does not occur at the reference building). Additional building efficiency options and solar water heating are employed until the marginal cost of saved energy for these options equals the cost of producing PV energy at point 3. The annual cost equals the annual cost of the reference building at point 4. From that point on, energy savings are solely a result of adding PV capacity until ZNE is achieved at point 5.

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 & 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, 10 or more categories.

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 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 to other target levels of energy savings between the reference building and ZNE and is the basis for establishing the optimal path to ZNE.

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 from discrete options in various categories. For example, options in the wall construction category may include 2×4 R11, 2×4 R13, 2×6 R19, 2×6 R19 with 1-in. foam, and 2×6 R19 with 2-in. foam.

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, energy use predictions, and other parameters, near-optimal points may be as good as optimal points. For various reasons unrelated to energy or cost, 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; others can be added with perturbation techniques.

4. BEOPT SOFTWARE

The BEopt software uses a sequential search technique to automate the process of identifying optimal building designs along the path to ZNE (4). The selection of this technique was influenced by several factors. First, the method identifies intermediate optimal points all along the path of interest (i.e., minimum-cost building designs at different target energy savings levels), not just the global optimum or the ZNE optimum. Second, the method allows discrete rather than continuous building options to be evaluated, reflecting realistic construction options. Third, near-optimal alternative designs are identified along the path, allowing for substitution of essentially equivalent solutions based on builder or contractor preferences.

The sequential search approach involves searching all categories (wall type, ceiling type, window glass type, HVAC type, etc.) for the most cost-effective combination at each sequential point along the path to ZNE. Starting with the reference building, simulations are performed to evaluate all available options for improvement (one at a time) in the building envelope, equipment, appliances, lighting, and solar water heating. Based on the results, the most cost-effective combination 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

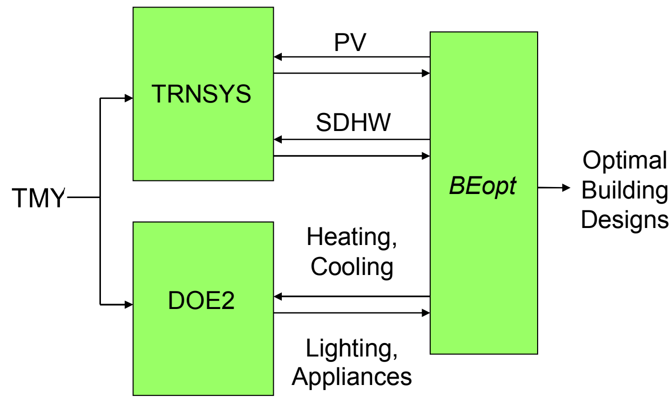

Fig. 2: Optimization with multiple simulation engines

the building envelope or equipment has a higher marginal cost, the building design is held constant, and PV capacity is increased to reach ZNE.

The BEopt software calls the DOE2 (5) and TRNSYS (6) simulation engines. TMY 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 and the database of performance characteristics published on its web site (8). Perfect maximum power-point tracking is assumed. The inverter efficiency is assumed to follow the shape of a typical inverter, with a capacity of 1.2 times the rated PV array output at standard rating conditions.

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 available for optimization.

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.

5. ASSUMPTIONS

5.1. Building Characteristics

A simple two-story 2,000-ft^2 home with an attached two-car garage was used for this study (Figure 3). The home has a slab or basement foundation depending on climate. Window area was assumed to be 18% of floor area. The study was limited to one orientation (back facing south), allowing full exposure of the windows on the back of the home to winter sun. Adjacent homes 10 ft to the east and west provide shading of sidewalls of the house analyzed.

The energy options considered in the study include space-conditioning systems, envelope constructions, hot water systems (including tankless and solar hot water), lighting systems, major appliances, and grid-connected residential PV. No specific options that address miscellaneous electricity loads other than major appliances were included in the study.

5.2. Economic Assumptions.

The homeowner costs calculated in the study assume a 30-year mortgage at a 7% interest rate, 3% general inflation rate, a 5% nominal discount rate, and a 30-year analysis period. The net present value of replacements for options with lifetimes shorter than 30 years were included in option costs.

5.3. Occupancy/Operational Assumptions

The occupancy and operational assumptions used in the study are defined in the Building America Research Benchmark (10) and include time-of-day profiles for occupancy, appliance and plug loads, lighting, domestic hot water use, ventilation, and thermostat settings.

5.4. Reference Building Characteristics

Incremental energy savings and incremental home costs are calculated relative to a reference building of the same size, geometry, and occupancy/operation as the design building, which meets IECC 2006 (10) requirements for the climates studied.

5.5. Cost Assumptions

Each option has an assumed first cost and lifetime. Costs used in the analysis represent retail costs and include estimated costs for hardware, installation labor, overhead, and profit. Construction costs (wall insulation, ceiling insulation, foundation insulation, etc.) are typically based on national average cost data (11). Window and HVAC costs are based on quotes from manufacturers' distributors. Appliance costs are based on manufacturers' suggested retail prices. Some energy efficiency option costs are based on a California database (12).

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 [CFLs]) are modeled based on cumulative hours of use. The home is assumed to have a gas water heater (or solar hot water heater with gas backup), a gas furnace, a gas clothes dryer, and a gas stove.

Utility costs based on state average prices (13) for electricity and natural gas are 0.082, 0.134, 0.085, and 0.079 $/kWh and 1.68, 1.22, 1.33, and 1.16 $/Therm for Phoenix, San Diego, Atlanta, and Chicago, respectively

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 operation and maintenance costs.

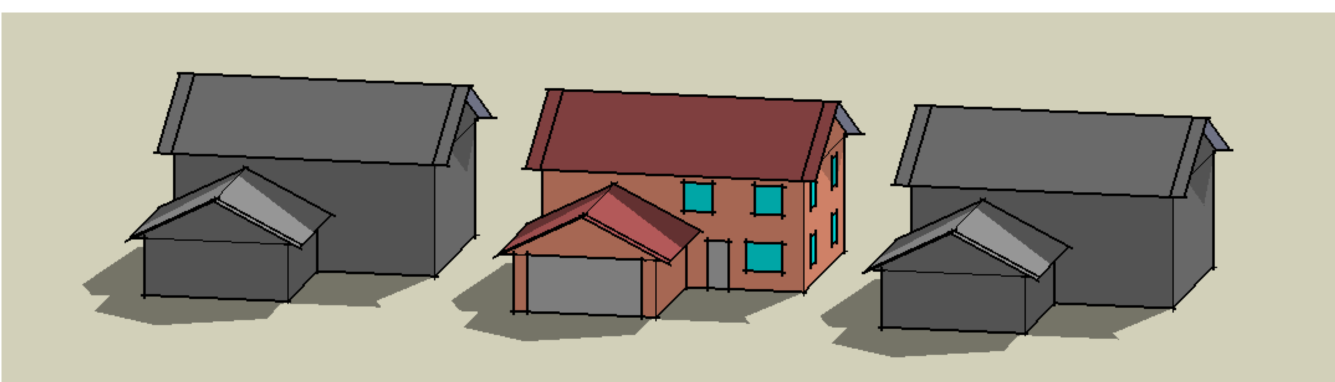

Fig. 3. House geometry with neighboring houses used for shading analysis.

6. RESULTS

6.1. Climate-Specific Results

Analysis results for Phoenix, San Diego, Atlanta, and Chicago are shown in Figures 4 through 7. All the figures include three specific graphs.

The upper left graph shows optimal and near optimal points along the path to ZNE. The x-axis displays the percent of source energy saved compared to the reference building. The y-axis shows annual energy-related costs including utility bills, the cost of efficiency measures included in the mortgage payment, and the present value of future replacement costs for options with lifetimes shorter than the analysis period. Each point represents an actual simulated building design. The curve connects the points with the lowest annualized energy cost for any given energy savings. The straight line sloping up to the right shows the addition of PV in 0.5-kW increments.

The lower left graph 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 reference building; the right-hand bar shows results for the ZNE point. Building source energy use (MBtu/year) consumption is shown on y-axis. The PV energy production is shown by the horizontal black line, and the net energy consumption (energy use minus PV production) is shown by the number in parenthesis – zero for the ZNE design.

The right-hand graph displays option data for the ZNE design. The range of possible options is shown in light gray, and the reference building option is shown in dark gray. The options for the ZNE design are shown in dark blue. Option names are shown to the right, and option costs are shown relative to the reference building.

6.2. Climate Comparison Results

Figure 8 shows combined results for all four climates. In the upper left graph, the path-to-ZNE curves are overlaid, and the reference building source-energy use and PV array sizes are shown for each climate. In the lower left graph, the end use graph shows results for ZNE designs for each climate.

The right-hand graph shows comparative options data for all cases. For the San Diego (user-selected as the base for comparison because it is the mildest climate), option data are displayed as in the right-hand graphs in Figures 4 through 7. For other climates, options are only shown if they are different than in San Diego with indicators (red and green bars) showing the direction and magnitude of the differences. Several of the differences shown in Figure 8 are simply the result of the fact that the Chicago building has a basement while the buildings in the other climates have slab-on-grade floors.

The following options were chosen for ZNE designs in all climates:

- window area – shifted to the back (south)
- appliances – high efficiency
- fixed and plug-in lighting – CFLs
- water heaters – tankless
- ducts – inside conditioned space
- PV size – sufficient for ZNE

Compared to San Diego, the other climates show:

- wall insulation – more in hotter/colder climates
- ceiling insulation – more, except Phoenix
- roof reflectance – more in hotter climates
- radiant barrier – only in Phoenix
- infiltration – tighter in hotter/colder climates
- slab insulation – more in Atlanta
- wall mass – more in colder climates
- window type – solar heat gain coefficient depends on climate
- dishwasher – less efficient in Phoenix
- air conditioner – higher SEER in other climates
- furnace – higher AFUE in colder climates
- mechanical ventilation – Chicago has heat recovery ventilator
- solar water heating – larger in colder climates

Many of these results are consistent with expectations as a function of climate characteristics. A few unexpected results, however, warrant further comment: 1) the less efficient dishwasher in Phoenix is perhaps due to lower hot water loads attributable to higher temperatures of incoming cold water (mains water temperature is a function of annual average ambient temperature); and 2) higher SEER air conditioners in colder climates are likely due to heating benefits from two-speed operation and high-efficiency fans that come with the air handlers associated with high-SEER air conditioners.

Table 1 shows results from Figures 4 through 7 for the four climates. The numbered columns (major headings) in Table 1 correspond to the design points in Figure 1.

Column 1 (reference point) shows source energy values ranging from 185 MBtu/year in Phoenix to 203 MBtu/year in Chicago, with a minimum for San Diego, which has neither the heating nor the cooling extremes of the other climates. Energy-related cash flows range from $1,450/year in San Diego to $2,100/year in Atlanta.

Column 2 (minimum cost point) shows lower energy savings relative to the reference building in colder climates. This is likely due to more stringent U-value requirements in the IECC 2006 in cold climates. The cash flows savings (which are maximized at this point) range from 15% in Chicago to 24% in Phoenix.

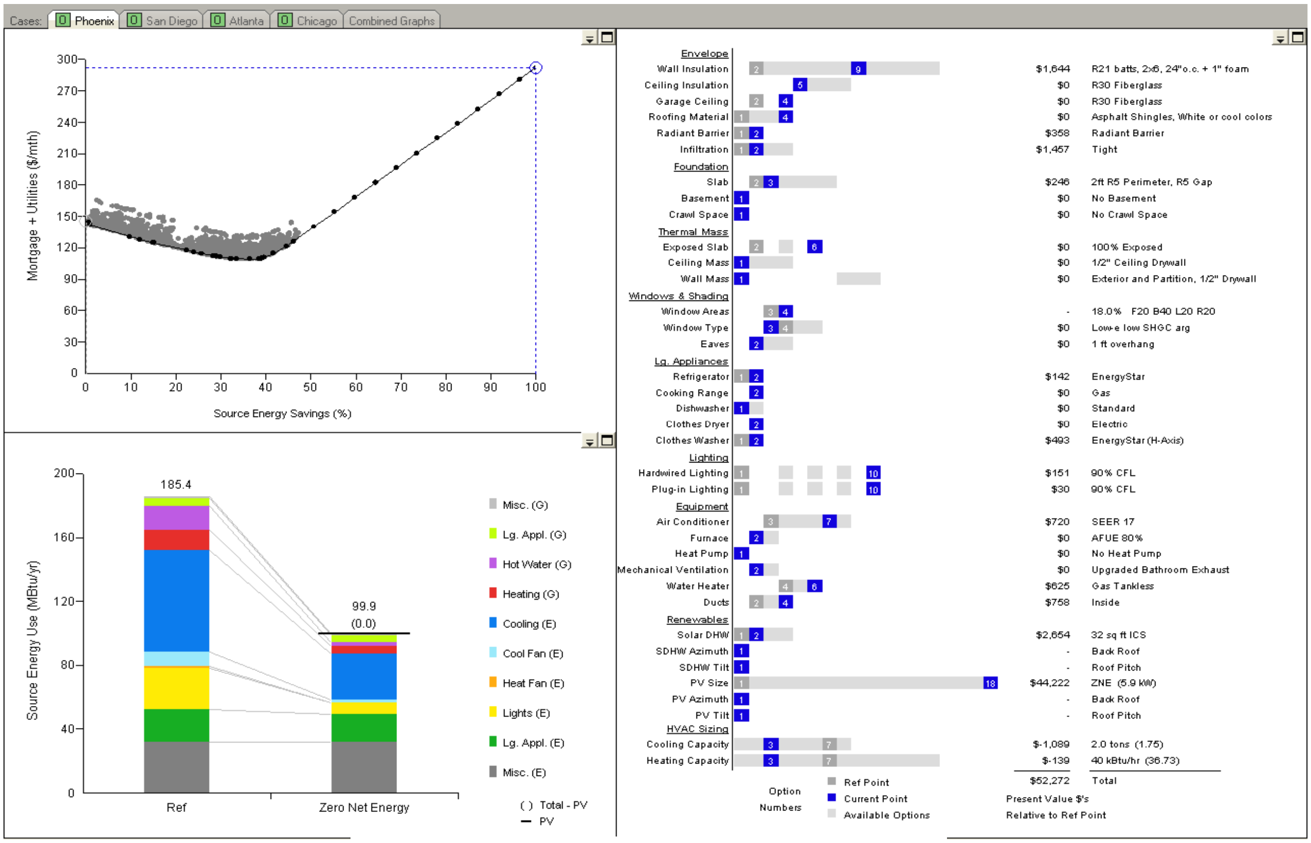

Fig. 4. ZNE results for Phoenix, Arizona.

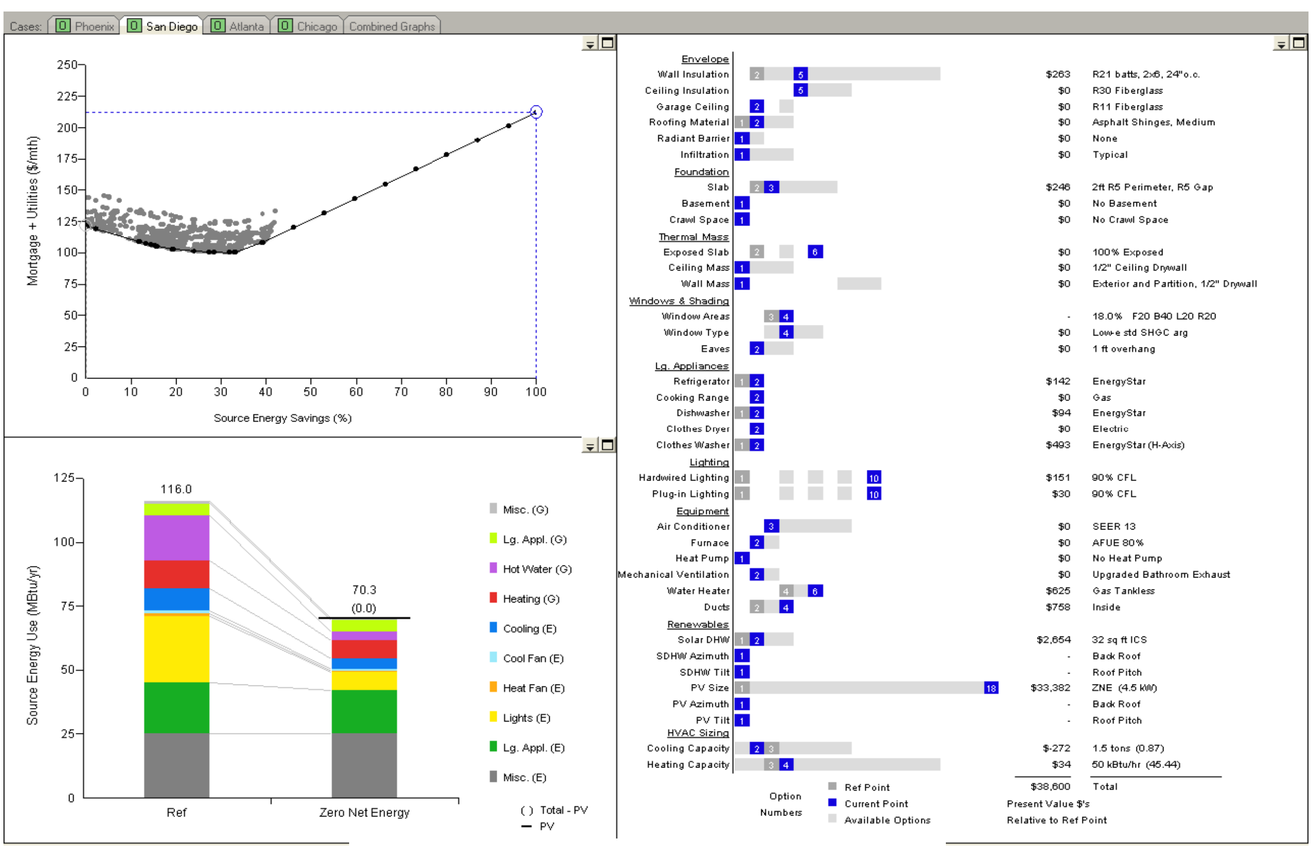

Fig. 5. ZNE results for San Diego, California.

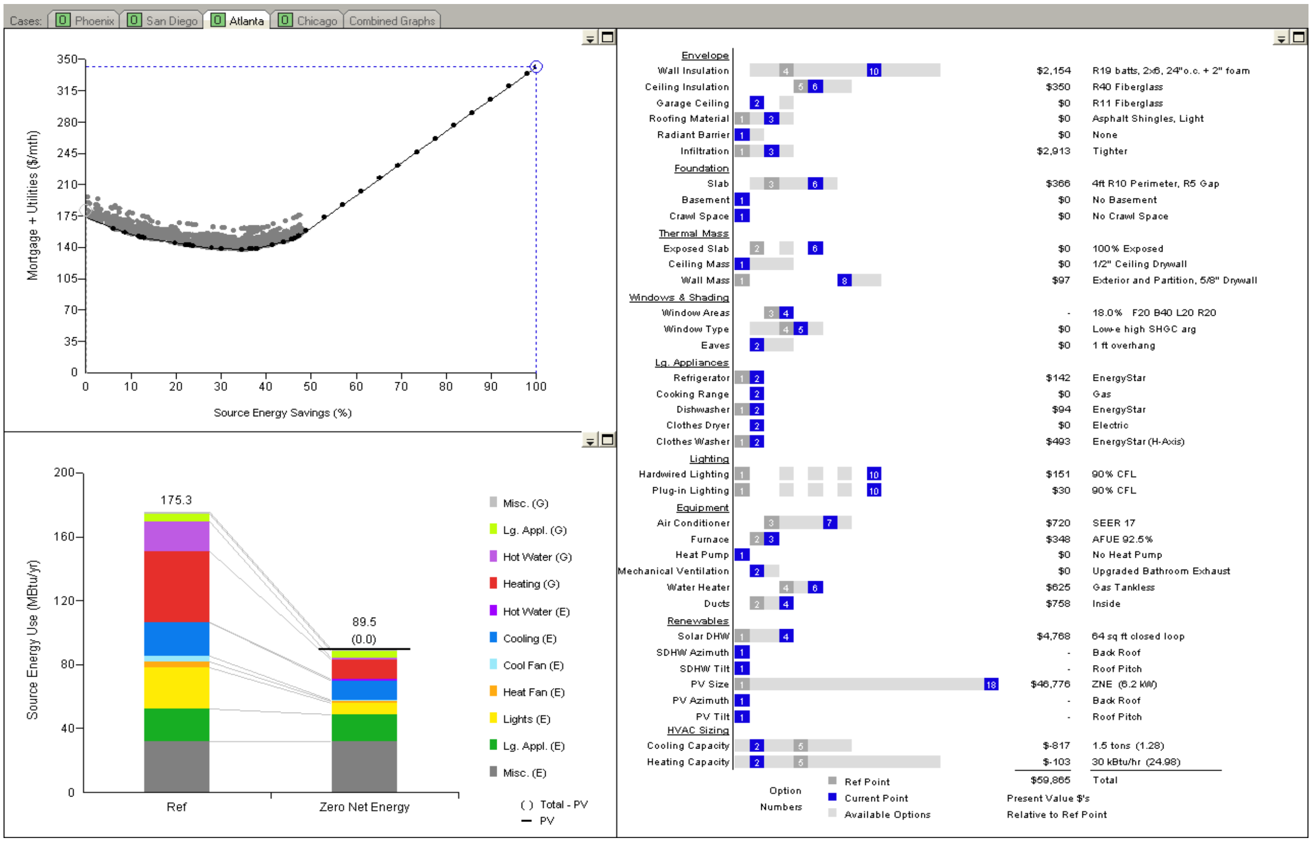

Fig. 6. ZNE results for Atlanta, Georgia.

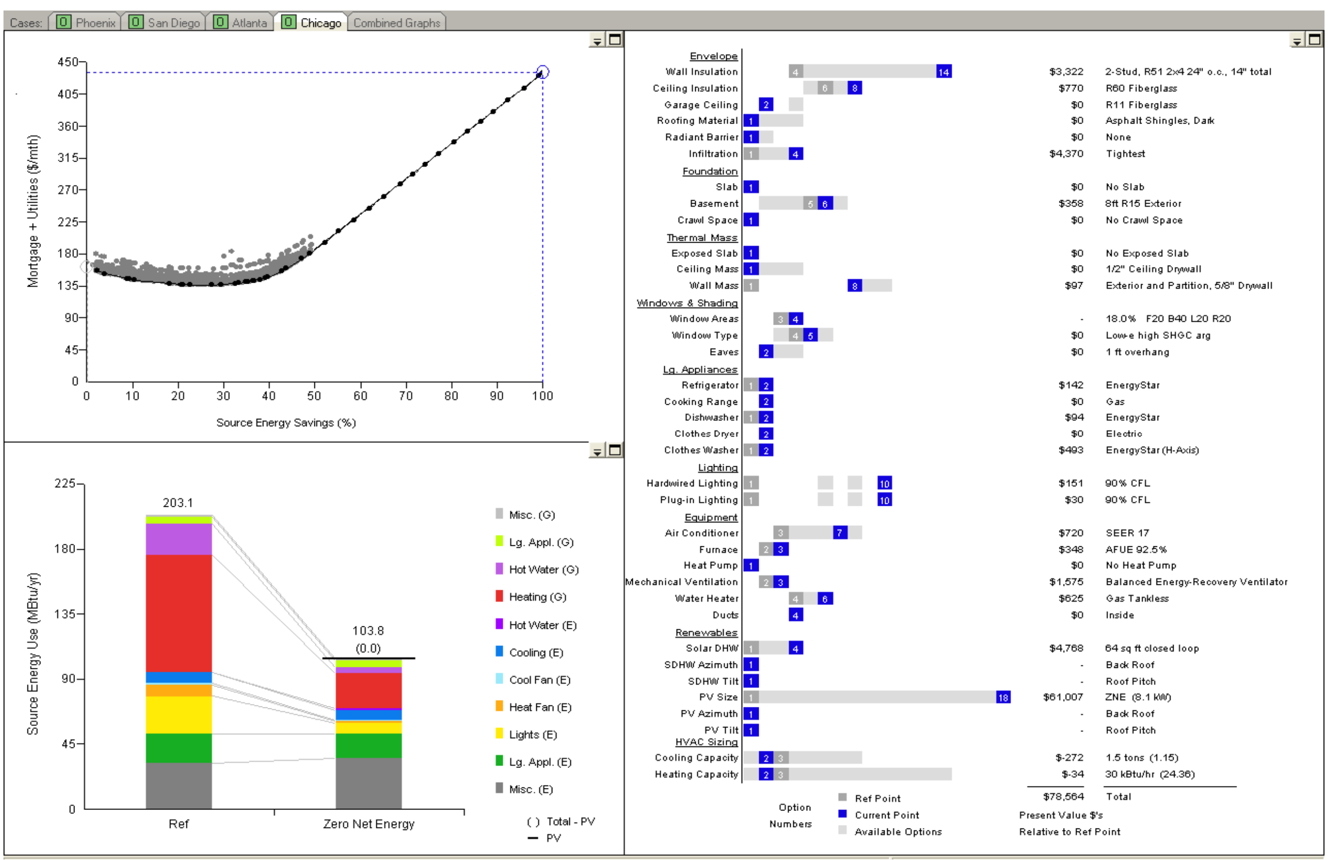

Fig. 7. ZNE results for Chicago, Illinois.

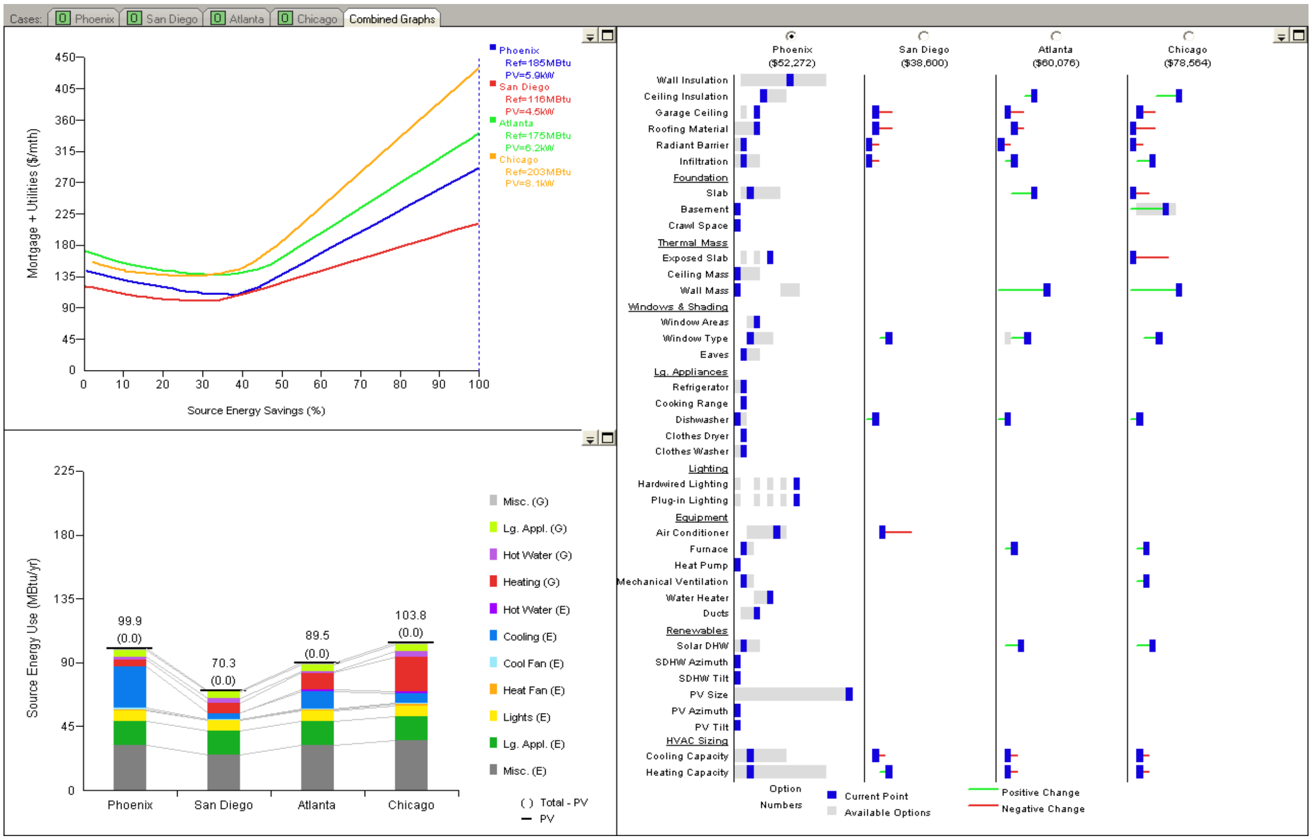

Fig. 8. Combined ZNE results for Phoenix, San Diego, Atlanta, and Chicago.

TABLE 1: SAVINGS IN SOURCE ENERGY AND CASH FLOW

	(1) Reference Point		(2) Min. Cost Point		(3) PV Start Point		(4) Break-Even Point		(5) ZNE Point		
	Source Energy (MBtu/y)	**Cash Flow ($/y)**	**Source Energy[1] (%)**	**Cash Flow[1] (%)**	**Source Energy[1] (%)**	**Cash Flow[1] (%)**	**Source Energy[1] (%)**	**Cash Flow[1] (%)**	**Source Energy[1] (%)**	**Cash Flow[1] (%)**	**Array Size (kW_{DC})**
Phoenix	185	1700	38	24	46	12	50	0	100	-106	5.9
San Diego	116	1450	32	17	40	12	46	0	100	-76	4.5
Atlanta	175	2100	34	21	49	10	53	0	100	-95	6.2
Chicago	203	1950	22	15	49	-10	43	0	100	-169	8.1

[1] Positive values indicate percent reductions relative to the reference building; negative values indicate percent increases.

Column 3 (PV start point) shows energy savings of 40 to 49% and cash flow savings of 10 to 12%, except for Chicago, where efficiency improvements continue beyond the break-even point and cash flow is 10% more than in the reference building.

Column 4 (break-even point) shows source energy savings ranging from 43% in Chicago to 53% in Atlanta at cash flows equal to the reference building cash flows.

Column 5 (ZNE point) shows source energy savings (100%), cash flows, and PV array sizes. The PV array size (kW) for each climate is a function of: 1) the local solar resource and 2) the PV energy needed to be supplied, i.e., the reference building source energy multiplied by (1 – percent savings at PV Start). Phoenix, of course, benefits from an excellent solar resource while San Diego has the smallest array size due to low overall building source energy consumption.

7. SUMMARY

Based on optimizations using the BEopt software for a 2,000-ft^2 house in 4 climates, we conclude that, relative to a code-compliant (IECC 2006) reference house, the following are achievable:

- Minimum Cost Point: 22 to 38% source energy savings and 15 to 24% annual cash flow savings
- PV Start Point: 40 to 49% source energy savings at -10 to 12% annual cash flow savings
- Break-even Point: 43 to 53% source energy savings at 0% annual cash flow savings
- ZNE Point: 100% source energy savings with 4.5 to 8.1 kW_{DC} PV arrays and 76 to 169% increase in cash flow

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

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