

## TOWARD ZERO ENERGY BUILDINGS: OPTIMIZED FOR ENERGY USE AND COST

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### ABSTRACT

To minimize energy use in a cost effective manner, an online building optimization tool is being developed to help compare distributed generation (DG) alternatives with energy efficiency measures. This tool is meant to provide information about building performance early in the design process for non-technical users.

Displaying capital cost above baseline as the independent variable, the tool outputs the net annual energy use and total cost for each case analyzed in the optimization. This allows the user to understand the range of technologies and cost involved along the path from the basecase to a zero net energy building (ZNEB).

### INTRODUCTION

Recently, there has been a push toward zero net energy buildings (ZNEBs). While there are many options to reduce the energy used in buildings, it is often difficult to determine which are the most appropriate technologies to implement. To reach zero energy, some designs extensively rely on the use of photovoltaics (PV) to meet the building load, without first exploring the benefits of deep energy efficiency measures.

To minimize energy use in a cost effective manner, an online building optimization tool is being developed to help compare distributed generation (DG) alternatives with energy efficiency measures. This tool is meant to provide information about building performance early in the design process.

To calculate building energy use, the tool uses Design Advisor, an online simulation tool that allows non-technical users to set up and run annual energy simulations in just a few minutes (Urban 2006). Design Advisor provides the capability to analyze a suite of energy efficiency measures such as insulation, window type, and schedules as well as green and cool

roofs. A DG model, which currently includes building integrated PV and combined cooling heating and power (CCHP), is being coupled with Design Advisor. Algorithms are then wrapped around these models to display the Pareto front of energy use and cost.

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### BACKGROUND: EXISTING TOOLS

There are a number of existing tools with similar objectives and features such as BEopt, OptEplus, GenOpt, DER-CAM and Homer.

#### **BEopt**

This software, developed by NREL, is designed to find optimal building designs on the way to a zero ZNEB. The user selects discrete options for various building options, then energy savings are calculated from a Building America Benchmark or a user-defined basecase. The software outputs the minimum building cost designs at various energy saving levels. A “sequential search technique” is used to find the most cost effective combination of energy efficient measures and PV (Christensen 2005).

#### **OptEPlus**

OptEPlus is a tool developed by NREL to run parameterized Energy Plus runs. Here, the user is able to modify parameters in an xml file, rather than individually altering the EnergyPlus input files, which can be very time intensive. While this is not an optimization tool, it is in the same family in that it can aid in the comparison of numerous design options (Flager 2008).

### GenOpt

GenOpt is a generic optimization program developed at LBNL that has implemented a number of optimization algorithms such as generalized pattern search and particle swarm. It is a stand-alone optimization program that is designed to be coupled with any simulation program that requires a text input. As in most building simulation, GenOpt is designed to work with programs where the derivative of the cost function is not available. GenOpt can handle both continuous and discrete variables and some constraints (Wetter 2004).

### DER-CAM

The Distributed Energy Resources Customer Adoption Model (DER-CAM) is an economic model that helps users find the least cost DG and/or CHP option for their site (in combination with the grid) (Siddiqui 2005).

### Homer

HOMER, developed by NREL, is an optimization model for distributed power. This tool can be used to find the least cost option to meet electrical and thermal loads with sensitivity analysis. However, this tool can only help to make choices between distributed generation choices and cannot optimize the design to reduce the load.

### Analysis of Existing Tools

While the existing tools are quite useful in certain applications, none of them has successfully balanced quickly optimizing both efficiency measures and varied distributed generation alternatives for various building types. BEopt is probably the closest, but it is only used for residential and solar applications with discrete choices. OptEPlus could provide the framework for comparing efficiency measures, but again the development of EnergyPlus models is time intensive, as well as computationally expensive to implement. GenOpt is quite useful for aiding in the optimization side of the problem, but still requires some other building model to run. DER-CAM and HOMER extensively cover the distributed generation field, but do not address the building efficiency side.

Therefore, a fast, online optimization tool that can be used by non-technical users to balance energy efficiency measures with DG options in both commercial and residential buildings would be a new addition to the field.

## MODELING

### MIT Design Advisor

The MIT Design Advisor is a web-based building energy simulation tool developed by MIT's Building Technology Lab (<http://designadvisor.mit.edu/design/>). Design Advisor aims to help reduce building energy demand early in the design process. The tool was designed to allow a non-technical user to quickly develop models and compare alternatives. This was a key shift in available modeling tools because energy modeling is usually too cumbersome to be included in the initial design phase--when major capital costs and energy loads are determined. Although the required inputs have been simplified, the results are still very accurate. The daylighting results were found to agree within 10% normalized error to LBL's Radiance (Lehar 2007). Using steady-state heat flow calculations, U-Values and Solar Heat Gain Coefficients were compared to LBL's WINDOW5 for a variety of glass types. While a few cases differed by 5 to 10%, most agreed to better than 1% (Urban 2007). Calibrated comparisons for heating and cooling loads were compared DOE's EnergyPlus with good agreement, although the models had to be simplified since EnergyPlus does offer many more options (Urban 2007).

As seen in Figure 1, the process used by this tool is inherently multidisciplinary. The user input, along with the appropriate weather file, is passed to the Daylight and HVAC Loads models. The Daylight Model calculates the available daylighting and passes artificial lighting demand needs to the HVAC Model. These models then output information about energy, comfort, and daylighting to the user.

The MIT Design Advisor calculates the HVAC loads through the energy balance method, accounting for heat exchange due to heating, cooling, ventilation, internal loads, and thermal mass, as well as heat exchange through the envelope of the building. The energy output results give the annual heating, cooling, and lighting needs. These numbers are given in terms of primary energy, so efficiency differences between gas and electric are accounted for. Therefore, in the optimization, we analyzed the sum of the heating, cooling, and lighting needs or the total annual energy use.

Several new modules are being introduced to the Design Advisor interface. Recently, the ability to study cool roofs and green roofs has been added. In addition,

modules for cost, PV, and CCHP are being developed.

### PV Model

A PV module was created to output a PV system’s capital cost and annual energy production given the system size and basic weather data. This model utilizes a method that inputs annual average daytime temperature and total irradiation data to determine the relative PV module efficiency for a given location (Huld 2008). In turn, this efficiency is used to predict the annual energy output from the cells. The cost model is based on a dollar per square foot (\$/sf) value. In our models, we’ve typically used values ranging

Variable	Description	Lower Bound	Upper Bound	Units
x1	Window-to-wall ratio	10	90	%
x2	Wall R-value	1	7	m <sup>2</sup> -°C/W
x3	N-S façade length	10	62.5	m
x4	Window type	0	2	single, double, triple
x5	Window coating	0	1	clear, low-e
x6	Thermal mass	0	2	zero, high, low

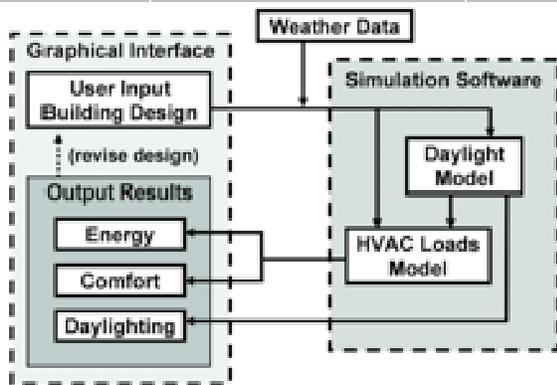


Figure 1: Schematic of MIT Design Advisor (Urban 2005).

### Efficiency Cost Model

Calculating the cost of a building is generally a complicated process involving factors such as material cost, installation cost, predicted energy use and prices, discount rates, etc.

To estimate the cost per unit area of energy efficient measures, we utilized RSMMeans data, in addition to manufacturer prices. This model was developed to compare an energy efficient building to a basecase. All of the cost equations are based on a change in a variable, rather than set prices. For example, the cost of adding wall insulation is found by multiplying a constant times the surface area times the change in R-value.

from \$4-8/sf depending on building type and tax credits.

The energy produced by the PV cells is used for lighting, cooling, and heating (through a heat pump). For initial studies, it was assumed that both the chiller and the heat pump had a COP of 3.

### Combined Cooling, Heating, and Power (CCHP) Model

A CCHP module was developed to output a CCHP system’s capital cost, operating cost, and annual energy production in the form of electricity and usable thermal energy. This thermal energy is used for space heating and cooling. To cool, the model assumes the use of absorption chillers with a COP of 1.2.

## OPTIMIZATION

### Algorithm

To begin to understand the solution space, we performed single objective optimizations for energy use and cost. In both cases, a genetic algorithm was used with varied population sizes and generations.

As expected from the formulation, the additional capital cost above baseline converged at \$0/m<sup>2</sup> when using a population size of 100 running for 50 generations. The sensitivity of the optimal solution to all variables was O(10<sup>-3</sup>) or less, therefore we expect that our optimal solution is stable (Lee 2008).

Due to extensive computational requirements, for the annual energy use optimization, we reduced the population size to 30 with 40 generations. This converged to 95.51 kWh/m<sup>2</sup> using only energy efficiency options (no DG) (Lee 2008).

To evaluate solutions of both objective functions simultaneously, we sampled a set of points between the solution points for each function. The Pareto front will be approximated by determining the set of points which were not dominated by any other point in the sample set.

### Building Model Emulator

While Design Advisor is fast enough to provide quick feedback in an online setting, to calculate annual energy use takes about a minute. As is, this would be prohibitively expensive to use as an objective function in an online optimization tool. Therefore, an emulator is being developed to allow objective function calculation time to be reduced to a fraction of a second.

The emulator uses pre-calculated results from Design Advisor to construct its rules, without reference to the equations of heat transfer used in the original model.

*“It is based on a linear regression technique, but rather than develop a single linear relationship between observed inputs and outputs from the physical model, a branching system of many linear classifications is employed, in order to accommodate potential nonlinearities in the original model at both fine and coarse scales. Fields of data points representing unique building cases from the physical model are distinguished through a series of partitions, with a Fisher Discriminant being used at each successive step to segregate cases into two groups. The classification scheme is then used to provide estimates of the output values most likely to result from a given vector of inputs to the physical model” (Lehar 2007b).*

### Initial Runs

Initial optimization runs were performed using 6 energy efficiency variables and 2 distributed generation options. This is an early run of the optimization and more design variables will be folded into the scripts in the future.

### Parameters

Site parameters include data about the site itself that cannot be changed. These include annual weather data (including average daily temperatures and average solar radiation), the latitude of the site, and the total

area of the plot available. The building type (office/residential) is also a parameter, affecting the minimum lighting levels required and the average power density of electrical equipment. Occupancy parameters include the total number of occupants using the building, their schedule, and the internal heat gains they produce. Setpoint temperatures for summer and winter are fixed at typical values. In this initial study, the values for these parameters are as follows:

- 1) Location: Boston, MA
- 2) Building Type: Office
- 3) Occupation Density: 0.1 person/m<sup>2</sup>
- 4) Occupation Schedule: 7am to 8pm
- 5) Minimum Lighting: 500 lux
- 6) Equipment Density: 5 W/m<sup>2</sup>
- 7) Square footage per floor: 625 m<sup>2</sup> (~6700 sf)
- 8) Average Room Dimensions: 5m x 5m x 3m high
- 9) Ventilation System: Mechanical Heating and Cooling (Chiller COP = 3, Furnace Efficiency = 100%)
- 10) Minimum Temperature: 20 °C (68 °F)
- 11) Maximum Temperature: 26 °C (78.8 °F)
- 12) Fresh Air Rate: 15 L/s-person (1.8 air changes per hour)

Initial tests of the model were completed on a sample low-rise commercial building in Boston. We ran these initial tests with PV at \$4/W and \$8/W (no tax breaks). In addition, we looked at net metering prices of \$0.1520 and \$0.10 per kWh. Discount rates were varied from 8% to 12%. And finally, we explored 5, 10, and 30 year projections.

### Constraints

The only equality constraint included in the optimization is the total square footage of each floor of the building. This constraint ensures that North-South façade length times the East-West façade length must remain constant. Additionally, there were also upper and lower bounds set on the continuous variables, which are discussed below.

### Design Variables

For initial test runs, we chose six design variables for the optimization, as shown in Table 1. The window to wall ratio (x1) describes the percentage of the exterior wall that is made up of windows. The upper and lower bounds for this variable illustrate feasible designs.

The wall R-value (x2) represents the level of insulation in the wall. The third design variable is orientation, which is represented as the length of the North-South façade (x3). One of the constraints was that each floor must be 625 m<sup>2</sup>, so the upper and lower bounds were based on feasible dimensions, with two rooms next to

each other as the minimum length (10m). The length of the East-West façade was a dependent variable based on the value of the North-South length and the desired square footage.

The window glazing type (x4) is a discrete variable that refers to the number of panes of glass in each frame. The window coating type (x5) is also a discrete variable, either clear or low-emissivity. Finally, the thermal mass (x6) refers to the construction material and its ability to absorb and release heat.

### INITIAL RESULTS

Figure 2 shows the standard output from the simulation runs. The top graph shows the total cost vs. the capital cost above baseline. The total cost is equal to the capital cost plus the NPV of the energy cost. In the axis, the baseline is at zero. The plotted points are separated into buildings that only employ energy efficiency measures, ones that use just PV, and ones that use both. The bottom graph shows the net annual energy use vs. the capital cost above baseline. The total cost of the system is low over 30 years due to the tax breaks on PV and the avoided energy costs over the years. However, to reach net zero energy (as seen in the points on the far right of the bottom graph), significant capital costs above baseline must be met.

Figure 3 and Figure 4 show the same building, but over 5 and 10 years, as opposed to 30 years. After 5 years of energy savings, the total cost of the system is still well above the baseline. However, with the PV tax breaks, Figure 4 illustrates that the total cost does go below baseline after 10 years.

In contrast, as seen in Figure 5 when the cost of PV is calculated without tax breaks, it takes 30 years to just break even on the total cost. And that is after investing extremely high capital costs. If the discount rates are higher, or the net metering buy back rates are lower, one simply cannot break even over the lifetime of the PV cells.

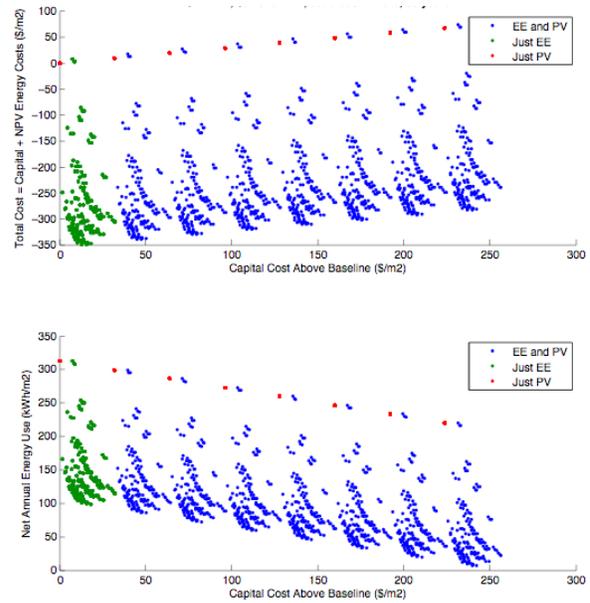


Figure 2: Simulation results for a low-rise commercial building in Boston. Assumed \$4/W PV, \$0.1520/kWh, 8% discount rate, 30 years.

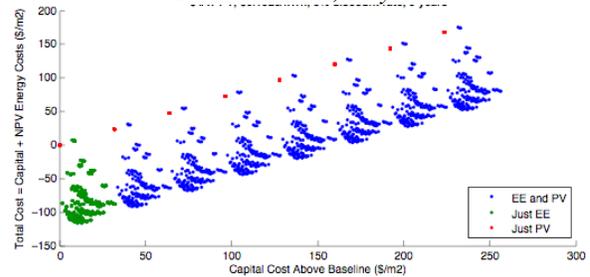


Figure 3: Simulation results for a low-rise commercial building in Boston. Assumed \$4/W PV, \$0.1520/kWh, 8% discount rate, 5 years.

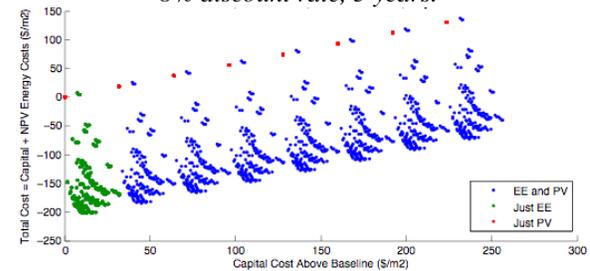


Figure 4: Simulation results for a low-rise commercial building in Boston. Assumed \$4/W PV, \$0.1520/kWh, 8% discount rate, 10 years.

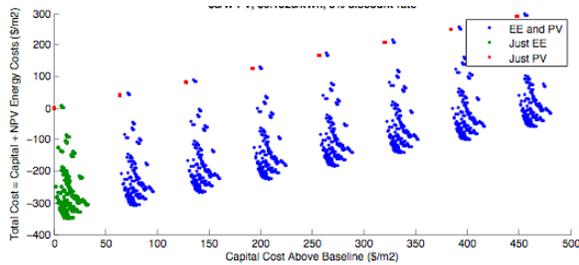


Figure 5: Simulation results for a low-rise commercial building in Boston. Assumed \$8/W PV, \$0.1520/kWh, 8% discount rate, 30 years.

## CONCLUSION

From the initial runs, as expected, it is clear that it is still quite expensive to achieve zero net energy when PV is the only DG choice. Even with tax breaks over 30 years, the overall cost of the building is more expensive than the basecase. When energy efficiency measures are implemented, then PV is added, the buildings become more affordable. With tax breaks, the payback takes about 10 years (30 years real price). However, these results are highly dependent on factors such as the kWh price and discount rate and more sensitivity analysis should be implemented.

These results are not at all surprising. However, the framework developed through this modeling process lays the groundwork for more interesting studies. In the current model, there is a vast cost difference between the efficiency measures and PV. However, as the efficiency and DG options are expanded, these tradeoffs will likely be more interesting and less intuitive.

## NEXT STEPS

This optimization tool is still in the development phase. We are currently working to complete the online implementation. Once the basic version is running online, we will begin to wrap in more modules and variables. CCHP, green and cool roofs, and natural ventilation are a few examples of variables that will be added. In addition, we will continue to work through various output options to best use the data from the optimization runs.

## ACKNOWLEDGMENT

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