CASE STUDY

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## 7 Steps to an Optimal House

ZEROs™ (Zero Energy Residential Optimization software) is a home design tool. Our goal is to guide a user to a home design that achieves their budget and sustainable living objectives. A common misconception in today's home construction field is that upfront cost for solar energy is "too expensive". ZEROs will dispel that notion by showing how a properly designed home will require relatively low capital investment while achieving a significantly lower lifetime cost. ZEROs also provides monthly cash flow (mortgage, tax, insurance and energy) information, which shows how construction cost and energy usage are translated into monthly expenditures. A properly designed, solar powered home will have a negligible monthly cost difference in comparison to a conventionally constructed home during the mortgage period, followed by lower monthly costs beyond the mortgage lifetime.

Confusion surrounds home design, and for good reason. Imagine exploring the effects of wall insulation thickness, ceiling insulation thickness, south window area, north window area, type of heating system, and so on. On top of this, each design aspect must be varied several times in order to gauge its importance on energy and cost. The multitude of design variations are in the millions. And, these design choices are interrelated. The optimal thickness of a home's insulation depends on the type of heating and cooling system chosen. For example, the most economical home with electric resistance heating will often have thicker insulation than the most economical home with a geothermal ("ground source") heat pump. Is the optimal home with electric resistance heating better or worse than the optimally designed home with a geothermal heat pump? Well, depending on climate, occupants, and other home design factors, either choice may be better. ZEROs has been created to help you answer these questions.

Our design philosophy at Build Equinox is to search for the most economical solutions that satisfy one's design goals and constraints. An uneconomical design is a waste of your time and money, and a waste of resources. ZEROs puts the designer in charge of the design process so that one can navigate to a preferred design while being able to view how these preferences impact cost and energy performance. If you spend too much time on the computer, you will have no time to spend on more important things such as making sure the house is built with quality and that it is constructed according to the intended design goals. ZEROs makes effective use of a home designer's efforts by providing essential cost and energy information in a relatively short time.

A series of seven example cases are used to illustrate our approach for using ZEROs to find cost optimal house design solutions. This initial case study series examines a home in Urbana Illinois, a region with significant winter heating and summer cooling loads. The design procedure we outline can be used anywhere, from Florida to Alaska. This procedure can be used for a broad range of homes from small studio apartments to mansions. ZEROs is useful for retrofits and new construction, and for examining "chunks" of a home, such as a bedroom or a kitchen. ZEROs includes the important effects of moisture and air quality, as well as properly calculating the impact of heat pump water heaters, CERV smart ventilation, and other air ventilation systems. ZEROs also includes “design day” heating, cooling, and latent capacity analyses, replacing the need for Manual J analyses.

You can actively follow our discussion by downloading the "csv" file that accompanies this note to your ZEROs account. A free subscription to ZEROs is available on our website (www.BuildEquinox.com/zeros). After starting up ZEROs, press the "Projects" button on the left side of the main ZEROs screen. Find the "Import Project/Case" button, and press it. You can browse your computer to find the csv datafile. After selecting this file, press the "Upload" button in ZEROs. A new project with the seven case files should appear in the Projects screen. Select any of these cases, and explore the input, output and module features on the left side of the screen. Change any of the input information, then press "Calculate" to see the how the change affects the various output results.

**Seven Steps Discussion Outline**

Our example house for this case study is a simple one. It has 2000 square feet of floor area with 2000 square feet of external walls and 2000 square feet of roof. Think of this as a ranch house that is about 40 to 50 feet in foundation length and width, with an average ceiling height of 10 feet. The volume of the house is 20,000 cubic feet. We will assume three occupants live in our example home. Our first two cases are for conventionally constructed homes with typical levels of insulation and sealing (6 inch wall insulation, 12 inch ceiling insulation, building infiltration sealed to 7 ACH at 50 Pa). Case 1 has no windows while the south wall (500 square feet) of Case 2 is completely covered by windows. Cases 1 and 2 provide extreme limits, with more moderately windowed homes falling somewhere in between these two cases.

All of our example homes assume an indoor temperature maintained at 72F. Monthly indoor humidity varies. The maximum indoor humidity allowed is 60%, which typically occurs during summer months. During other months when infiltration, ventilation and occupancy results in indoor humidity less than 60%, the moisture is allowed to "float" such that neither humidification nor dehumidification are required. ZEROs allows users to change the monthly indoor temperature and humidity, providing the energy impact of these important effects to be investigated.

Cases 1 and 2 help establish a reference to today's construction in terms of energy usage, lifetime cost and cash flow (monthly cost). Cases 3 through 7 progress from Case 1, our windowless home, in order to find the most economic version of that home. We progress through stages that improve the home's performance in the following manner: Case 3 assumes the house is tightly sealed and a fresh air ventilation system is installed; Case 4 converts the home from a conventional electric water heater to a "heat pump water heater"; Case 5 alters the wall and ceiling insulation to economically optimal levels; Case 6 adds a solar PV electric system sufficient for achieving "net zero" house energy operation; and Case 7 adds 3kW of solar PV for powering an electric vehicle (EV).

Cases 3 through 7 are for a windowless home. Windows are expensive façade coverings of a house. A proper discussion of windows includes daylighting and aesthetics, which detract from our current objectives. After moving through Cases 3 through 7, try adding windows to the different sides of the home. “Good” windows are Energy Star level while “Super” windows are characteristic of higher performance windows (eg, triple glazed with low conductivity gas fills and vacuum deposited low emissivity coating for a lower loss coefficient). “Good” windows cost $30 to $60 per square foot while “super” windows cost $50 to $100 per square foot. A window area that is 10% of the house floor area is a good target for excellent daylighting, view and aesthetics (that is, about 200sqft for the example home). Many of today’s “solar” homes exceed 20% window to floor area ratios, which result in poor economic and energy performance due to the high capital cost of windows, and the need for high capacity heating and cooling comfort conditioning equipment. For northern locations, locating more windows on the south side provides some winter energy benefit, but the benefit is generally not sufficient to pay for the windows over their lifetime.

**Case 1 and Case 2 Discussion: How do windowless and heavily windowed homes compare?**

Home designers are often under the mistaken belief that windows significantly improve energy efficiency and will "payback" their cost over time. South facing windows may provide some improvement in energy usage when properly specified for northern climates, however, their cost effectiveness is almost always poor. Cases 1 and 2 illustrate the characteristics of a home with no south window area versus a home with a maximum amount of south facing window area. A heavily windowed home is one with a window area that is more than 10% of the floor area. Case 2 assumes 500 square feet of "good", Energy Star level windows, or 25% of the floor area.

Annual electric energy usage for Cases 1 and 2 are 12,336kWh/yr and 11,696kWh/yr. The south windows reduce the annual utility cost by $84/yr assuming an electric utility rate of $0.13/kWh. Monthly energy tables in the ZEROs pdf reports (and in the monthly energy tables under the Output Overview tabs in ZEROs) show a significant shift from energy required for heating the house in the winter to energy required for cooling the home in the summer. Examination of the Life Cycle Cost (LCC) for Cases 1 and 2 shows the windowless house to have a 100 year lifetime cost of $412,736 while the windowed home has a lifetime cost of $495,543, indicating that the windowed home is much more expensive over its lifetime than the windowless home.

Note that our LCC assumes no time value of money. That is, no inflation, discount, escalation nor other types of monetary rates are assumed. Without a time value of money, one is assuming that the relative cost of different factors such as energy or a replacement window are the same in the future as now in relative terms. Replacement costs are included in the ZEROs Economics input screen. Windows, for example, might have a lifetime of 20 to 30 years (warrantees are typically 10 years). Water heaters might last 15 years, and so on. The assumed house lifetime (100 years for our case series is assumed) is used for the overall LCC basis. An item such as an air conditioner with an assumed lifetime of 20 years would be replaced 5 times over the home's assumed life. Details of assumed cost parameters used for the LCC analyses are contained in the Economics section of the left side menu bar. Also notice within the Economics section an "LCC Outputs" selection that provides cost details beyond the overview summary screen.

We find that the capital cost of the windowless home is $213,574 versus $239,171 for the heavily windowed home. Most of the investment cost is for the base house, assumed to cost $100 per square foot. The base house cost includes any of those items not related to the home's performance such as kitchen cabinets, internal walls, bathrooms, etc. Items in the base house cost are "fixed" cost items that do not impact the optimizing of a home's energy performance. There may be other cost related assessments that should be performed, but these are independent from the energy related assessments that ZEROs performs. For example, the choice between a steel roof and an asphalt tile roof is one of higher initial cost (steel) versus higher lifetime cost (asphalt lifetime of 20 years versus 50 years for steel) Asphalt shingles have disposal costs while steel roofing is recyclable with a salvage value.

Beyond the house base cost are the additional costs for energy related items such as insulation, windows, solar panels, and home conditioning systems. Approximately $22,000 of the windowed Case 2 capital cost is for the windows, which are assumed to cost $45 per square foot (typical of good quality, Energy Star level windows). Case 2 also has an additional $5000 expense for increased heating and cooling equipment capacities. Windows increase **both** summer cooling capacity and winter heating capacity requirements. The ZEROs report results show "design day" heating and cooling capacity requirements. Two heating and two cooling capacity levels are listed in the ZEROs output "summary overview" page. One capacity is for cloudy or nighttime periods and the other capacity is for sunny day time periods. For heating season requirements, the cloudy day capacity is used to size heating requirement needs. During a cooling season, the sunny day capacity is used to size cooling capacity requirements. The "latent" (moisture) conditioning design day capacity is also shown, which is combined with the heating or cooling capacity information in order to determine total comfort conditioning requirements.

Notice that Case 1's cloudy and sunny day time periods results in the same winter heating capacity and summer cooling capacity requirements. A house without windows does care if the sun is shining. The windowed Case 2 shows that a cloudy winter day requires a higher heating capacity than a sunny day, while a sunny summer day requires more cooling capacity than a cloudy day. Case 1's design day heating requirement is 5.9kW and design day cooling requirement is 2.5kW. Case 2 requires 8.4kW for heating on a cold, cloudy day, and 8.7kW for cooling on a sunny, summer day. One should also note that these extremes in conditioning capacity are also felt by the occupants. Windows reduce the thermal massiveness of a home and tend to create significant temporal and spatial variations in a home's comfort, even though on average, the home's interior is "comfortable".

ZEROs provides information on "financing" a home. An economically optimized home may not be an "affordable" home. ZEROs estimates expected monthly cash flow for different home designs. The Finance section of ZEROs (left side menu bar) contains assumed financial parameters and financial results. The windowless home will cost $1532 per month with an average monthly utility cost of $154. Case 2 has a monthly cost of $1714 per month with an average utility bill of $147 per month.

**Case 3: Highly sealed home with fresh air ventilation system**

The conventional homes in Cases 1 and 2 are reasonably well sealed by conventional construction standards. The assumed infiltration blower door test level of 7ACH at 50 Pa (ACH=air change per hour; Pa = Pascals of pressure difference) is sufficient for keeping carbon dioxide and other pollutants at reasonable levels without adding a fresh air ventilation system, however, "sufficient" should not be construed as meaning it provides a healthy indoor environment. Older homes typically range from 10 to 30ACH, while the new generation of high quality, energy efficient homes have infiltration leakage that are less than 1ACH. The cost for achieving a highly sealed home is negligible. The cost to highly seal Equinox House to a level below 0.6ACH at 50Pa was \$500, consisting of \$250 for caulk and tape and \$250 for labor (10-12 hours at \$20 per hour). Overly complex construction methods and complicated detailing of meaningless features can make effective house sealing very expensive. Keep things simple.

If you change the blower door parameter in Case 1 to 0.6 from a value of 7 in the "Envelope" setup tab in ZEROs, and then press the Calculate button, the impact of low infiltration can be viewed directly. The estimated annual home electric energy usage drops to 10,240kWh as shown on ZEROs' "overview" tab (see the summary page). Average indoor air quality shown on the overview summary page estimates a carbon dioxide concentration of 5200ppm, which is extremely poor air. More than 60% of the population would agree that the air inside the house stinks. Carbon dioxide levels exceeding 600ppm (fresh air is 400ppm) impairs cognition in various manners (concentration, decision making, problem solving, etc). High carbon dioxide levels are also an indicator of increased concentrations of chemical and biological agents.

A "blower door" test is a common test used to determine the sealing of a home or building. The test consists of setting up a blower in an external doorway. The blower's pressure versus flow characteristics are calibrated. Current standards dictate running the blower at a speed that maintains a 50 Pascal (about 0.007psi or 0.2 inches $H_2O$) pressure difference between the house interior and exterior ambient. The measured airflow rate is used to determine the "ACH" (Air Changes per Hour) by dividing the flow by the house volume. Our Case 1 with an ACH of 7 and a house volume of 20,000 ft3, for example, has a blower door air flow rate of 2330cfm (cubic feet per minute; 7 x 20,000 / 60). The sealed home's 0.6 ACH has a blower air flow rate of 200 cfm. A "rule-of-thumb" for determining infiltration air flow through a house at "normal" pressure differences is to divide the blower door air flow by 20. Therefore, the Case 1 home has an infiltration air flow rate of ~120cfm while the sealed home has an infiltration of 10cfm at normal house pressure differences. Note that infiltrated air is not fresh air. A leaky house does not have fresh air. Leaky house air passes through flaws in the house envelope where it picks up mold, mildew, and vermin waste in an uncontrolled manner that leaves some home areas stagnant and polluted.

The LCC is significantly lower (\$378,000) than Case 1 due to less energy usage associated with lower infiltration. But, the house is not livable. Even though carbon dioxide is odorless, at this level, other chemical and biological concentrations will also be high ... and odorous. In order to make the home healthy, fresh air must be brought into the house. ZEROs allows the user to examine different types of residential fresh air ventilation systems that help manage the air quality of a home.

A "CERV" (Conditioning Energy Recovery Ventilator...see our BuildEquinox.com website for more information) is a special system that actively manages indoor air pollutants. The CERV uses a small heat pump for energy exchange between fresh air and exhaust air streams. Other ventilation system options are HRVs (Heat Recovery Ventilators) and ERVs (Energy or Enthalpy Recovery Ventilators). Note that one does not always want to "recover" or exchange energy between indoor and outdoor air streams. The CERV determines when outside air is more energy efficient to condition than inside air, and when energy exchange is a benefit. It also includes "DCV" operation (Demand Control Ventilation) with CO2 and VOC sensors that monitor and trigger fresh air ventilation as needed. Common HRV and ERV systems have rudimentary fan speed controls or simple programmable ventilation schedules that require occupants to guess air quality levels.

A CERV system adds a capital cost of $4500 to the home while HRV and ERV systems often range from $2000 to $3000 in capital cost. The capital cost of a CERV can be added by selecting the "Economics" tab on the left side of the ZEROs screen. Input a cost of $4500 for a CERV fresh air conditioning system under the "Ventilation System" icon. An expected CERV lifetime of 25 years (indicating four replacements over the 100 year expected life of the home) is reasonable relative to expected lifetimes of similar heating and cooling equipment.

In order to add a CERV to a home in ZEROs, go to the "Systems/Energy" tab and then select the "Ventilation System" input tab at the top of the ZEROs screen. Select a CERV in the system selection icon, and then set the indoor air quality setpoint to 900ppm of carbon dioxide. Press the "Calculate" button on the left side of the ZEROs screen, and go to the output overview screen. The windowless home now requires an estimated 10,605kWh of electric energy per year. The small annual energy difference from a highly sealed home with no fresh air is due to the CERV's heat pump efficiency during portions of the year when it is providing most of the home's comfort conditioning energy. The CERV's heat pump efficiency is quite high during moderate times of the year (spring and fall), often exceeding the efficiency of the heat pump performance assumed for the example cases. The CERV's controller also includes logic that knows when outdoor ambient conditions are better (more energy efficient) for conditioning the home than indoor air. When this occurs, most commonly in the spring and fall, the CERV brings in additional fresh air, equivalent to opening windows automatically.

The LCC is now $407,036 with a house capital cost of $217,775. Monthly cash flow is predicted to be $1544 with an average utility bill of $135 per month. Case 1's monthly cash flow is $1532, so for $12 per month, one can have a home that is more energy efficient and much healthier.

At this point, we see that our Case 3 home is quite similar to the Case 1 home in LCC and monthly cost. But, are things really the same? Here are a few significant differences between the conventional home and this super-sealed, fresh air home:
1) The CO2 level in the "leaky" conventional home (~800ppm) seems quite good....in fact better than the CERV home with a setpoint of 900ppm, but it is not. First, where the leaks are and where you live are two different things, resulting in high localized CO2 and other indoor contaminant concentrations. Second, "infiltrated air" is not "fresh air" as previously mentioned. It is air leaking through cracks and construction flaws in the home. Cracks are where mice, insects and various vermin live and defecate. These cracks and flaws are also the regions where the pesticide guy sprays his stuff. And, these cracks and holes are places where water

condenses at various times of the year, producing mold and mildew that affects your health and degrades your home's structural integrity. You should not breathe infiltrated air....but most people do in their homes. A properly designed fresh air ventilation system purges a house with air from a known source that is delivered to the places in the home where you live. A properly designed fresh air system also exhausts air from the moist and odorous regions (kitchen, baths, laundry, etc). Respiratory illnesses have doubled over the past two decades (nearly 10% of the population) at a time when smoking, auto exhaust, and industry pollutants are diminishing. Commercial buildings have fresh air supplied due to building code regulations. Homes have not had fresh air requirements. Our homes are making us sick in increasing numbers as they are better sealed without adequate provisions for fresh air.

2) Although the LCC and monthly cash flow appear similar, Case 3 requires more effort in the form of additional labor (manufacturing and installation of the fresh air system components). Lower utility bills offset the higher capital expenditure. A shift of dollars from utility cost to manufacturing and labor costs is a benefit to society. Anytime a dollar for conventional energy (centralized power plants, fossil fuels, etc) is shifted to products that make a home more efficient, jobs are produced. The conversion of fossil fuel dollars to products such as more efficient heat exchangers and solar panels results in a factor of 10 in job creation. Corporations that "make" things employ 3 people per million dollars of revenue while conventional energy companies employ less than 0.3 people per million dollars of revenue. Again, you won't feel the difference in your checkbook, but this shift of dollars will be felt in your local community and the country as a whole.

3) Poor air quality results in more sick days. The value of a sick day is approximately $200 per day ($25/hr, average US labor cost) plus costs for medications and doctor visits. The average daily energy cost for conditioning our sealed home with fresh air ventilation is $3.40 (9600kWh per year / 365 days per year x $0.13 per kWh). Being sick is expensive while the daily energy requirements of a high performance home are similar to the cost for a cup of coffee.

**Case 4: Addition of a heat pump water heater**

A relatively new product is the "heat pump water heater", which is basically a small window air conditioner mounted on top of a water heater tank. A heat pump water heater (HPWH) takes energy from the surrounding air and "pumps" it into the water tank. On average, a heat pump water heater will use less than 50% of the energy of a conventional water heater tank. The portion of a window air conditioner that exhausts heat from your house to the outside is instead connected to a heat exchanger that transfers energy into your hot water.

In southern locations without significant winter heating requirements, a heat pump water heater provides a duel benefit of cooling and dehumidifying your home while producing hot water. In northern climes, it may seem odd to "cool" your house during the winter, but it is not. During the winter, heat removed from inside your house for heating water is equivalent to the heat your body's metabolism puts into your house. Yes, your body heat over the course of a day is sufficient to heat an average person's 18 gallons of daily hot water from 50F to 120F. Does your body overheat your house? The cooling impact of a heat pump water heater is similar to your body's heating effect.

The heat pump water heater's cooling effect scales with occupancy. If no one is home, the water heater does very little other than make up for "standby" losses. If your house is filled with overnight guests, you'll enjoy the extra cooling and dehumidification as it produces extra hot water. During the winter, the extra cooling load is made up for by the home's space heating heat pump. This is what we call a "two-stage" heat pump. The house heat pump is optimized to heat your home from outside temperatures to inside temperatures while the water heater system is optimized for moving heat from indoor house temperatures to hot water temperatures.

For Case 4, go to the Systems/Energy input tab, and change the water heater COP (coefficient of Performance) to "2". A COP of "1" is a regular electric water heater that converts 100% of electric energy input into heat. We thermodynamicist types consider an electric heating efficiency of 1 to be a horrible thing to do to the well-ordered nature of electric energy. Electric energy can efficiently move things around. When used with a heat pump, we are able to move more "thermal energy" than simply degrading electricity with a resistance heater. A COP of 2 means that only half of the tank's hot water energy was electric energy. A COP of 3 (which is more similar to heat pump water heater performance...I assumed a value of 2 in Case 4 in order to be conservative) means than only a third of the electric energy of a standard water heater is used. The other change to make in Case 3 is in the cost of a water heater (see the Economics tab). Currently, a heat pump water heater costs $900 at your local Big Box Hardware Store while a conventional water heater costs $400. Installation costs are the same for each type of water heater.

So, is this significant? Examining the annual energy in the summary overview page, we now require 9070kWh of annual electric energy versus 10,605kWh found for Case 3. This is a nice drop in annual energy requirements. If we view this energy savings in terms of transportation, it is equivalent to the energy required to drive an electric vehicle 5000 to 6000 miles per year!

Examining the economic performance of the home, we find that the LCC is now $390,410 for a drop of $17,000 over the 100 year estimated house lifetime. Think of this money as extra cash in someone's pocket that they can spend on other things. The house capital cost is now $218,275, or roughly the cost difference ($500) between the conventional and a heat pump water heater. Again, the money paid for manufacturing products (the heat pump added to the water heater) rather than energy results in a net employment gain.

Note that the heating and cooling system capacities change from Case 3 due to the heat pump water heater's addition to winter conditioning needs and reduction of the summer cooling load. The total heating and cooling system capital costs do not change significantly. The heating system capacity requirement increases by 300Watts while the cooling system capacity decreases by 200Watts (see heating and cooling system capacities in the ZEROs overview summary tables).

**Case 5: Economic optimization of wall and ceiling insulation**

You will find people bragging over the amount of insulation they have shoved into their home. But is more better? Energy-wise, it often is but interestingly, even on a pure energy basis, one can find an optimal level. Think of wearing a coat. Is a thicker coat always better? Definitely not. You dress to the weather. At some point, you will overheat if your coat is too thick relative to your body's energy output and the temperature that you feel most comfortable at (a skin temperature of 80 to 86F). Similarly, a highly insulated home can be fully heated during some times of the winter by its internal heat generation sources (you, your computer, cooking, appliances, candles, and anything else releasing heat into the home). But, does this balance occur on February 3, or March 25, or ....? It is a rare occasion when stars align perfectly such that a home's insulation level results in no energy required for maintaining comfort in a home.

Economics will generally dictate an optimal solution before you reach a potential optimum condition based on energy. And, the world runs on economics. People and corporations naturally seek the most "economic" solution. We are now at an important crossroad where renewable energy and energy efficient homes compete with the economics of conventionally built homes. Economically efficient homes tend to be the most resource efficient design as well.

Case 5 differs from Case 4 by the thicknesses of the wall insulation and ceiling insulation. In either Case 4 or 5, examine the cost of insulation in the Economics tab. Wall insulation often costs more than ceiling insulation because some method is required for building a structure or casing for holding the insulation material. Insulation, such as "blown cellulose" (chewed up newspapers .... what happens when newspapers no longer exist? ... maybe we'll return to eel grass, which was popular in the early 1900's until a blight hit eel grass growing regions), can more easily be applied to the attic space of a home, resulting in lower cost per volume than wall insulation. The cost assumed for our wall insulation is $5 per cubic foot, which is a reasonable cost for styrofoam as used in SIPs (Structural Insulation Panels) and ICF (Insulated Concrete Forms), two modern wall construction methods that lead to easy-to-seal home envelopes. A cost of $2 per cubic foot is assumed for the ceiling insulation, similar to cellulose blown into an attic space.

The overview summary page of ZEROs has some red and green up/down "sensitivity" arrows that we have been ignoring until now. These direction arrows indicate good (green down arrow) or bad (red up arrow) directions in terms of LCC or annual energy. In Case 4, you will see that both the LCC and annual electric energy arrows are green and point down, indicating that an increase in insulation thickness will lower both LCC and annual energy usage.

More detail about the home's cost sensitivity and energy sensitivity are shown in the Economics tab under "LCC Outputs". An extra inch of wall insulation added to the Case 4 home will reduce the house LCC by $2898 and reduce annual electric energy by 226kWh per year. An extra inch of ceiling insulation will reduce the LCC by $672 while decreasing annual energy cost by 61kWh per year. Case 5 shows the results of increasing the wall and ceiling insulation thicknesses to a point where the LCC arrows change from green to red. If you increase either the wall or ceiling insulation thickness by an inch, the associated green LCC arrow will turn red. Examining the more detailed sensitivity analyses information under the LCC Output in the Economics tab shows that the LCC cost and annual energy impact of more insulation are not very significant. Compare the impact of an extra inch of insulation with the cost of adding 10 square feet of windows or the impact of an additional occupant in the home.  Notice a reduction of 50W of occupant power usage and an occupant hot water reduction of 1 gallon per day are very significant.

It turns out that the optimal insulation thickness effect on LCC cost for many climatic regions is not very strong near the optimum level.  In this example, our optimal walls are 13 inches thick and our optimal ceiling insulation is 21 inches thick.  Comparing our Case 5 optimized home to Case 4 with conventional insulation levels, we have dropped another 1200kWh per year, which would provide an additional 4000 miles of EV driving. The LCC dropped from $390,410 to $379,590 as we thickened the insulation.  Our capital cost increased to $226,065 from $218,300, which impacts monthly cash flow.  Monthly expense is now $1576 (with $105/month for utilities) as compared to $1531 per month for Case 4 (and $118/mo utilities).  Although the monthly expense is higher, the home's owners will recoup the cost after the mortgage is paid off due to the lower monthly utility cost.

Note that these dollar magnitudes are quite small when comparing the impact of windows in Case 2.  Also, notice that the window sensitivity arrows all show that the addition of 10 square feet of window on any face of the house will increase the LCC.  That is, windows will not improve the home's economic performance.  The green sensitivity arrow for the south facing window's annual energy indicates that some addition of south windows will lower energy due to winter heating potential, but not in an economical manner.  Our ZEROs window case study will explore this effect in more detail.  Windows should be selected for "light and delight" rather than for perceived cost benefits.

The final steps consist of examining the economic feasibility of adding a solar PV (photovoltaic) system.  The green LCC and annual electric energy sensitivity arrows under the solar PV area item should have caught your attention by now.   If not, take a look at Case 5 again.  Ten square feet of solar PV collector area will lower our LCC by $500 and our annual electric energy by 166kWh per year.  If you want the most economical home, solar PV will be part of its design.

First, we'll examine sufficient solar PV system size to bring the home to "net zero" energy.  Then, we will add an additional amount of solar energy that can be used to power a family's EV for 12,000 miles per year.

**Case 6: An economical net zero home**

Moving Case 5 to Case 6 only requires adding a solar PV system. What about solar thermal energy systems? Solar thermal energy systems, such as water heating systems, cannot compete on efficiency, cost, or practical (that is, minimum headache frequency) bases. So, we have excluded solar thermal energy systems from our simulation modeling. Our bias toward solar PV for residential energy applications is rooted in extensive solar thermal experience. In the cold world of economic reality, it is only a matter of time before the rest of the world learns this truth.

The Solar tab provides solar PV system input and output information. Various parameters can be selected, however, the defaults for cost, orientation, collector efficiency (Watts per square foot) are all reasonable with today's silicon PV technology. We only model south facing collectors, which is reasonable if you are +/-30 degrees of due south. For more accurate modeling, use some of the online software, such as NREL's (National Renewable Energy Laboratory) "PVWatts" programs.

Here's a simple solar system sizing rule-of-thumb that will get you close to the answer for most of the country. Divide your annual electric energy requirement by 1.25 to get a reasonable estimate of the solar collector array's rated "wattage". Our optimized Case 5 house needs 7900kWh per year. Our rule-of-thumb indicates that a 6300Watt solar array is in the appropriate range. In either Case 5 or Case 6 ZEROs file, change the solar system size to 6300Watts. You will find that the system oversupplies the house needs by an estimated 150kWh....a small value. Reducing the solar array by 100Watt increments will show that a 6000Watt rated solar PV array will be the economic optimum. Note that in the Economics tab, we have assumed that electricity has a value of 13 cents per kWh, and has zero value for any excess solar energy produced. Some utilities (such as Illinois under current law) are allowed to zero any energy surplus accrued at the end of the "utility year" (April). Other states and utility systems (such as electric co-ops that are under federal regulations rather than state) will write a check to the homeowner for energy surpluses.

Under the Solar tab, with a 6000Watt solar PV array, we find that it will require about 450 square feet of area (less than the size of a garage roof). The conventional home of Case 1 would need nearly 800 square feet of roof space for net zero operation. The projected cost of our optimized installed array is $27,000. With a 30% federal tax credit, the net solar array cost is $18,900. The assumed unit solar array cost used in ZEROs is $4.50 per Watt, which is a conservative (high) estimate. If you are getting installation estimates higher than this, get other bids. Our numbers are based on real costs. Current installed costs, if you know what you are doing, are now $3 per Watt. Less than $1.50 per Watt is required for the solar panels and inverter, and the other $1.50 per Watt is for collector mounting rack, wiring, disconnect switches, and labor (what is called BOS, or "Balance of System" costs). Notice that at $3 per Watt, we no longer need the federal tax credit.

Let's see how the cost of this capital investment compares with our other cases. Our LCC has plunged another $24,000 from $379,590 to $355,800. The solar powered home requires $244,965 to capitalize, which results in a monthly cash flow of $1595 per month during the mortgage lifetime. A monthly utility bill of $21 per month is due to the utility company's monthly "customer service fee". We have assumed a "grid-tied" solar system in which we use the electric grid to shuttle energy to-and-fro from the grid. Although utilities continue to grumble about some of the solar buyback regulations, they are getting a good deal as they sell our excess daytime solar energy produced during peak time periods for a good profit.  Also, utilities gain solar residences as customers at night when they are looking for customers to keep their baseload plants operating.

Compared to the do nothing, conventionally-built Case 1 house, our monthly cash flow has increased by $63 per month during the mortgage lifetime.  But, remember that we have not assumed any energy cost escalations.  The sun's energy cost will not escalate, but utility costs will.  As previously discussed, this increase is small compared to poor decisions in house design being made every day.

**Case 7: Solar powered transportation**

Evaluating the cost of solar powered transportation adds another dimension to the cost effectiveness of our home. Current EV (electric vehicle) technology achieves 3 to 4 miles per kWh of electrical energy (charge station efficiency is included). The cost of solar electricity is now ~10 cents per kWh (from Case 6, divide the $18,900 net solar PV system cost by 7647kWh of annual electric energy production and divide that answer by 25 years for the warranted solar system lifetime.). Assuming 3 miles per kWh and 10 cents per solar generated kWh, our solar powered driving cost is 3.3 cents per mile. The US fleet average mileage is ~27 miles per gallon for combustion powered cars. Assuming $3.50 per gallon (yes, about 40 cents per gallon is for state and federal taxes, but there are other "hidden" taxes related to oil usage that are more than this) for a cost of 13 cents per mile. We can convert our fossil fueled vehicle cost to an equivalent electric energy cost, which results in solar generated electricity having a gasoline value of 39 cents per kWh. In order words, for every 3 to 4 miles of solar energy powered EV transportation, we save 25 to 30 cents in fuel cost.

In Case 7, 26 cents per kWh of value is used for the excess value of solar generated electricity used for vehicle transport. In this manner, we are assuming that our transportation costs are being kept equivalent to what they had been with fuel purchases, and then pocketing the net solar savings. An additional 3000Watt of solar PV array is assumed, which generates 3700kWh of additional energy that powers 12,000 miles of EV transportation per year. We now need 700 sqft of roof area for our 9000Watt solar array, which is still a small fraction of our total roof area (2000 sqft).

On the economic side, our LCC is now $297,000, or a drop of $116,000 from the conventional, Case 1 home with an average, fossil fueled vehicle. Our monthly cash flow is now $1566, due to a savings of $80 per month in gasoline (excess electricity valued at 26 cents per kWh). Alternatively, one could consider the value of the excess solar energy to be zero, and add $130 per month to Case 1 for its 1000 mile per month gasoline bill. Although the monthly cash flow is $32/month more than the initial conventional case without windows, notice that the solar power home with solar powered transportation is much lower than the Case 2 window home. That is, there are savings, such as in window design, where one can easily make up this difference without sacrificing aesthetics, features nor function.

EVs currently have a premium price tag (about $10,000), similar to flat screen TV technology when it first entered the market. EVs are a simple vehicle technology. As manufacturing efficiency increases, EV prices will decrease and auto manufacturer profit margins will increase to levels that exceed profit margin for complex internal combustion engine technology.

**Summary:**

So what's next? Hopefully this trip through Cases 1 to 7 has provided some familiarity with ZEROs as well as an understanding for designing economically optimal, sustainable, healthy and comfortable homes. But, there is a lot more. Who wants to buy a house with no windows? So, what is a reasonable design solution that includes windows. And, how do things change if we are interested in some other comfort conditioning systems such as "geothermal" or electric resistance heating? Does size matter? What are the differences between Florida and Arizona? Or, New Orleans and Minneapolis?

Additional case studies will explore these effects while providing more experience in how to use and interpret ZEROs modeling results.