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The Race to Zero: Carbon Neutral Construction for Residential Buildings

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Humanity's impact on the environment is one of the issues at the forefront of the concerns of society. As more environmentally conscious generations become homeowners, there will be a trend towards the development and purchase of carbon neutral houses. This case study is based on 3D renderings produced from BEopt^{TM} (Building Energy Optimization), a software developed by the National Renewable Energy Laboratory in support of the U.S. Department of Energy. The software provides a detailed simulation-based analysis that shows the affects that varying construction materials have on the energy consumption of a home. It also shows the how different climates impact that energy requirements of a home, and highlights the importance of location when creating a property that is carbon neutral with a net-zero energy consumption. By taking the insulating materials used to construct the home, and increasing their capacity to resist heat flow; the energy demands of a home can be lowered enough to be fully met by the inclusion of solar panels. To compensate for the carbon emissions shown by the BEopt analysis, terrestrial sequestration can be used. The use of a single acre of land for tree planting can sequester enough carbon to fully offset the yearly carbon production of the home. This case study is an analysis on the feasibility of producing a single-family, residential property that is carbon neutral with a net-zero energy consumption in the United States.

Keywords and phrases: carbon neutral, net-zero energy, residential construction, carbon sequestration, electricity, solar power, environment, architecture

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Introduction

The impact that human beings produce on the global ecosystem is vast. People have developed a way of life that requires massive amounts of electricity to be sustained. While the electricity that people rely so intently on provides innumerable benefits, it also comes at great cost. Energy produced and consumed by humans results in the release of carbon emissions into the atmosphere. These carbon emissions have been related to a great many negative impacts on the environment. In the last several decades, an increasing number of standards and initiatives have been introduced to promote the construction of environmentally friendly structures that produce lower carbon emissions.

Residential construction has been focused on by many organizations and communities. Germany was one of the pioneering nations to develop standards for carbon emissions in housing. Research done by Voss, Karsten, Musall, and Eike (2013) shows that one-third of German carbon emissions are produced by buildings, with twenty percent being solely produced by residential structures.

Because of the sizable percentage of carbon emissions that is controlled by residential structures, the Passive House Institute [PHI] was established in Germany during the late 1980's. Williams (2012) discusses two standards established by the PHI: the Low-Energy Standard and the Passive Standard. The Low-Energy Standard is met by a home that consumes 65kWh/m^2 per year, while the Passive Standard needs a much lower 15kWh/m^2 per year. Since the inception of the PHI and its standards, thousands of projects have been completed with their standards being used; also, there has been an American adaptation of PHI standards governed by the PHIUS.

This case study is an analysis of a 3D model of a residential building rendered on Building Energy Optimization (BEopt™) software. This model shows the energy requirements that a house design would have, and allows the user to alter components of the house to potentially lower the energy needs of the building. This case study utilizes the customization of the following building components within the BEopt™ software: building orientation, shape, size, use of space, location, construction materials and solar panel usage. By altering these components, this study shows various possibilities for the level of energy efficiency in the design of a house.

The goal of this study is to produce a design for a house that is as sustainable as possible, while being large enough to accommodate a single-family occupancy. The design should meet PHI standards, while also having net-zero energy consumption and carbon neutrality. By lowering the energy usage of the house, the levels of carbon emissions also drop. The carbon footprint can be made small enough to be balanced by having a single acre of land committed to terrestrial sequestration. The final design is for a low-energy property that relies solely on energy produced on-site, as well as sequestering all carbon that is emitted on a yearly basis.

Overview of Design

BEopt™ generates a 3D model of a home based on a floor plan that the user draws in a provided grid. The orientation of the building can be changed; this allows the building to face an optimal direction for collecting solar power during the day. Also, the space usage within the home, the number of floors, the size of the walls and the pitch and type of roof are all components that can be altered to create a multitude of varying projects.

This project was made with the intention of accommodating a four-person household. The building footprint encompasses 1656 square feet (sf), and contains 2300 sf of finished space. The space for the first floor of the home is used as living space, as well as space for the garage (Figure 1). The roof is a gable styled roof, with a 1:1 pitch. It is designed to be built with cantilevered trusses.

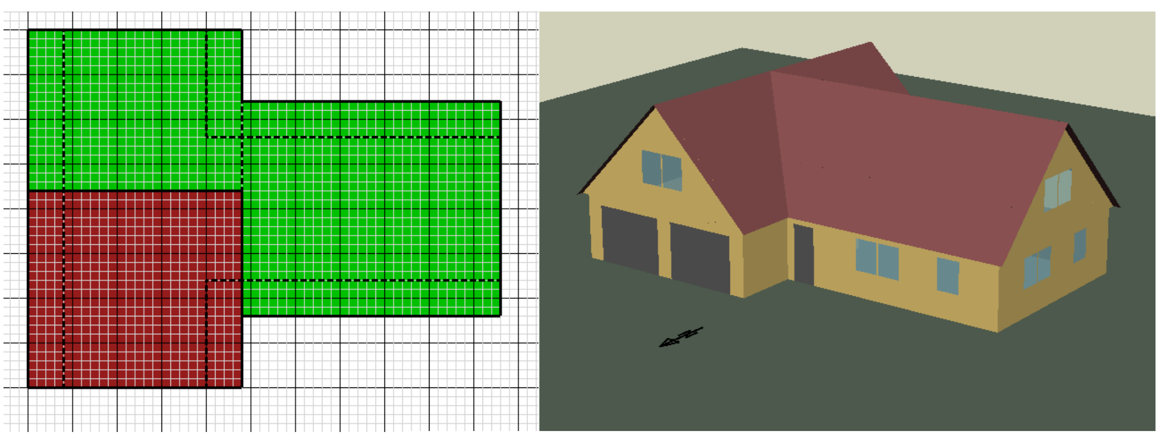

Figure 1. First floor of the design. The green area represents living space, while the maroon area represents garage space.

The basement level of this project is comprised of three components: 696 sf of unfinished basement, 432 sf of crawlspace and 528 sf of finished slab (Figure 2). The slab section is used underneath the garage of the home to provide the proper foundation to provide storage for vehicles. The basement is designed so the interior height of the walls is eight feet, while the interior height of the crawlspace walls is four feet.

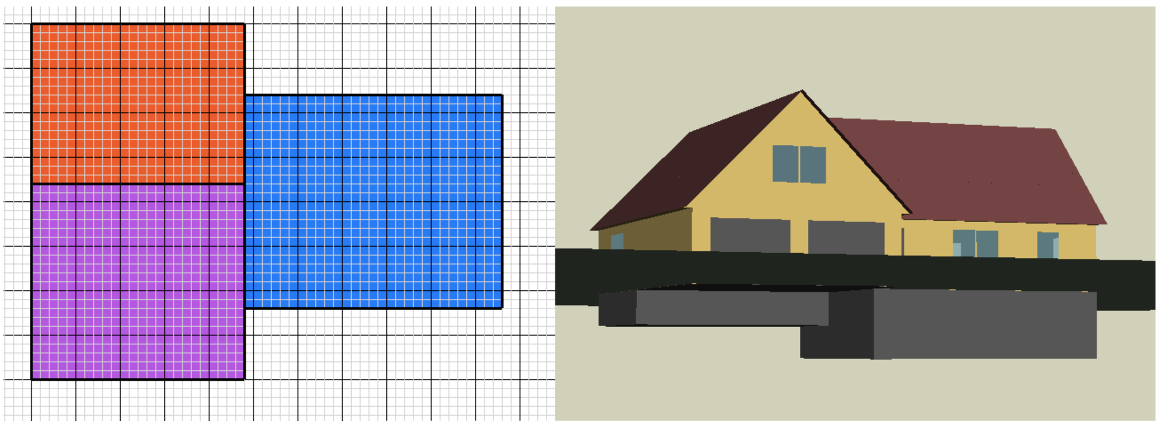

Figure 2. Basement floor of the design. The blue area represents unfinished basement, the red area represents crawlspace, and the purple represents finished slab.

The second floor of this project has three types of areas: 1168 sf of finished attic, 136 sf of garage roof space and 352 sf of unfinished attic (Figure 3). The second floor was designed to give the home a finished upstairs area that has walls instead of having the floor extend to the edge of the roof's slope. The interior walls are four feet high at their shortest, and twelve feet high at the peak of the ceiling.

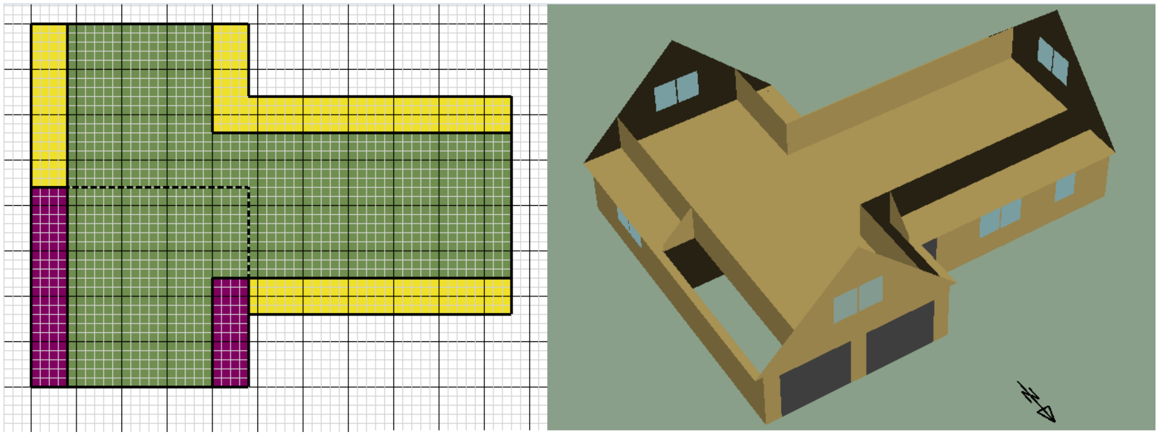

Figure 3. Second floor of the design. The green area represents finished attic, the yellow area represents unfinished attic, and the purple represents garage roof space.

This 3D model represents the overall layout and function for the design of this project. The variations being used for this analysis come from changes to the building materials being implemented in the design, as well as the inclusion of various photovoltaic [solar panel] systems. The floor plan and the usage of the space within the home remains the same across all cases to highlight the impact that the building's location and materials make on the energy consumption of the home.

Material Variation

This project consists of four different cases. Each case represents the design of this project being constructed with a separate set of building materials. The first case is a design labeled as **Base**; this design represents a baseline for the analysis, it uses traditional building materials seen in residential buildings that are not built with high levels of energy efficiency as a goal. The energy consumption for this design can be used as a bench mark to show how much the changes implemented in the other cases compare to the average home. It also shows the feasibility of producing enough energy for net-zero energy consumption with implementation of solar panels on a design with typical building materials.

The second case is designated as **Cheap**. This design was created by implementing the use of the cheapest materials possible, with no emphasis being put on lowering the energy demands of the home. This case shows the affects that cheap materials have on the energy requirements of the home. Lower-priced materials generally make poorer insulators. Because of this poor insulation, the heating and cooling system must work more often, resulting in increased energy consumption and carbon emissions.

The third case in this project is **Energy Efficient**. The purpose of the Energy Efficient design is to get the project within the PHI standards, without expending more money than necessary on efficiency. This case emphasizes the use of energy efficient appliances and conditioning systems.

The fourth and final case in this project is the **Expensive** case. The Expensive case forgoes all concern for the price of the building materials, focusing solely on lowering the energy requirements of the home. By using the best possible insulators available, this case shows the lowest possible energy requirements for the home in this project.

The options for the materials in BEopt^{TM} are grouped into sixteen categories: building, walls, ceilings/roofs, foundation/floors, thermal mass, windows & doors, airflow, space conditioning, space conditioning schedules, water heater, lighting, appliances & fixtures, appliances & fixtures schedules, miscellaneous, miscellaneous schedules, and power generation. Within these sixteen categories, there are 88 subgroups with nearly 1000 individual options to choose from. Each subgroup contains a list of individual options (Figure 4). The subgroup lists allow the user to compare similarly functioned building materials. The user can compare the insulating capacity of each material as well as the material costs associated with them.

Heating and cooling requirements represent the greatest possibility for lowering energy requirements in residential buildings. A large-scale Swedish endeavor to renovate apartment complexes to the PHI standard found that a proper plan for the conditioning system was essential for the success of that project. The work by Friesen, Malbert and Nolmark (2012) showed that, "a passive solar construction has a highly insulated, airtight building envelope, and

Option	R-Assembly [h-ft^2-R/Btu]	Cavity Insulation Type	Cavity Insulation Nominal R-value [h-ft^2-R/Btu]	Cavity Insulation Installed R-value [h-ft^2-R/Btu]	Cavity Install Grade	Cavity Depth [in]	Insulation Fills Cavity	Framing Factor [frac]	Framing Spacing [in]	Cost [$/ft^2 Exterior Wall]
1) None										
2) Uninsulated, 2x4, 16 in o.c.	4.0					3.5	False	0.25	16.0	$1.84
3) Uninsulated, 2x6, 24 in o.c.	4.1					5.5	False	0.22	24.0	$1.76
4) R-7 Fiberglass Batt, 2x4, 16 in o.c.	9.3	fiberglass batt	7.0	7.0	1	3.5	False	0.25	16.0	$2.36
5) R-11 Fiberglass Batt, 2x4, 16 in o.c.	10.9	fiberglass batt	11.0	11.0	1	3.5	True	0.25	16.0	$2.48
6) R-13 Fiberglass Batt, 2x4, 16 in o.c.	11.9	fiberglass batt	13.0	13.0	1	3.5	True	0.25	16.0	$2.54
7) R-15 Fiberglass Batt, 2x4, 16 in o.c.	12.7	fiberglass batt	15.0	15.0	1	3.5	True	0.25	16.0	$2.60
8) R-19 Fiberglass Batt, 2x6, 24 in o.c.	16.0	fiberglass batt	19.0	17.3	1	5.5	True	0.22	24.0	$2.65
9) R-21 Fiberglass Batt, 2x6, 24 in o.c.	17.7	fiberglass batt	21.0	21.0	1	5.5	True	0.22	24.0	$2.71
10) R-13 Cellulose, 2x4, 16 in o.c.	11.9	cellulose	13.0	13.0	1	3.5	True	0.25	16.0	$2.58
11) R-13 Cellulose, 2x4, 16 in o.c., Grade 2	11.4	cellulose	13.0	13.0	2	3.5	True	0.25	16.0	$2.55
12) R-13 Cellulose, 2x4, 16 in o.c., Grade 3	10.8	cellulose	13.0	13.0	3	3.5	True	0.25	16.0	$2.53
13) R-19 Cellulose, 2x6, 24 in o.c.	16.8	cellulose	19.0	19.0	1	5.5	True	0.22	24.0	$2.68
14) R-13 Fiberglass, 2x4, 16 in o.c.	11.9	fiberglass	13.0	13.0	1	3.5	True	0.25	16.0	$2.39
15) R-19 Fiberglass, 2x6, 24 in o.c.	16.8	fiberglass	19.0	19.0	1	5.5	True	0.22	24.0	$2.53
16) R-23 Closed Cell Spray Foam, 2x4, 16 in o.c.	15.3	closed cell spray foam	23.0	23.0	1	3.5	True	0.25	16.0	$4.07
17) R-36 Closed Cell Spray Foam, 2x6, 24 in o.c.	23.0	closed cell spray foam	36.0	36.0	1	5.5	True	0.22	24.0	$5.69
18) R-13 Open Cell Spray Foam, 2x4, 16 in o.c.	11.9	open cell spray foam	13.0	13.0	1	3.5	True	0.25	16.0	$3.31
19) R-20 Open Cell Spray Foam, 2x6, 24 in o.c.	17.3	open cell spray foam	20.0	20.0	1	5.5	True	0.22	24.0	$4.33

Figure 4. The Wood Stud subgroup within the Walls category. There are nineteen options for this subgroup. The walls used for the Energy Efficiency case in this project is highlighted.

uses an air-to-air heat exchanger for heating and ventilation. The idea was to wrap the house in an air barrier, install extra insulation on the walls, build in the balconies, replace the windows, and put on a new facade material" (p. 118). The same principle applies to a single residence: to reduce energy demands, provide increased insulation and efficient conditioning.

A material's insulating capabilities are quantified by its R-value. R-value is a measure of a material's ability to resist heat flowing through it. As the R-value increases, the thermal performance of the insulation improves. The efficiency of the conditioning system in a home is also quantifiable. The Seasonal Energy Efficiency Ratio (SEER) rating is a metric used to show the proportion of thermal units produced compared to the amount of energy required to run the system. As the SEER rating increases, a conditioning system requires less energy to produce the same results. The cases in this study that have the highest R-values and SEER rating, have the most expensive costs associated with their building materials, but the lowest energy requirements and carbon emissions (Table 1).

Table 1
R-value and SEER Variations

	Wall R-value	**Ceiling/Roof R-value**	**Floor R-value**	**Basement R-value**	**Crawlspace R-value**	**SEER Rating**
Expensive	50.7	61.6	28.7	21.8	28.1	24.5
Energy Eff.	23.1	39.4	25.2	16.7	15.6	18
Base	14.6	14.3	18.7	6.3	3.1	14
Cheap	10.4	8.7	14.6	3.1	3.1	13

Location Impact

To find the effect that the location has on the energy requirements, the cases were simulated in three locations with varying climates: Los Angeles, Phoenix and Chicago. Simulating this project in Phoenix and Chicago show the feasibility of net-zero energy consumption in hot and cold climates, respectively. Los Angeles represents a climate that requires relatively little indoor adjustment for home conditioning. Beopt^{TM} analyzes climate data from various locations in the United States to provide accurate expectations of the impact that climate has one the energy demands of a home.

In Phoenix, Arizona, only two cases where able to meet the net-zero energy consumption benchmark: the Energy Efficient and Expensive cases (Figure 5). While the Phoenix location produced more on-site electricity than the

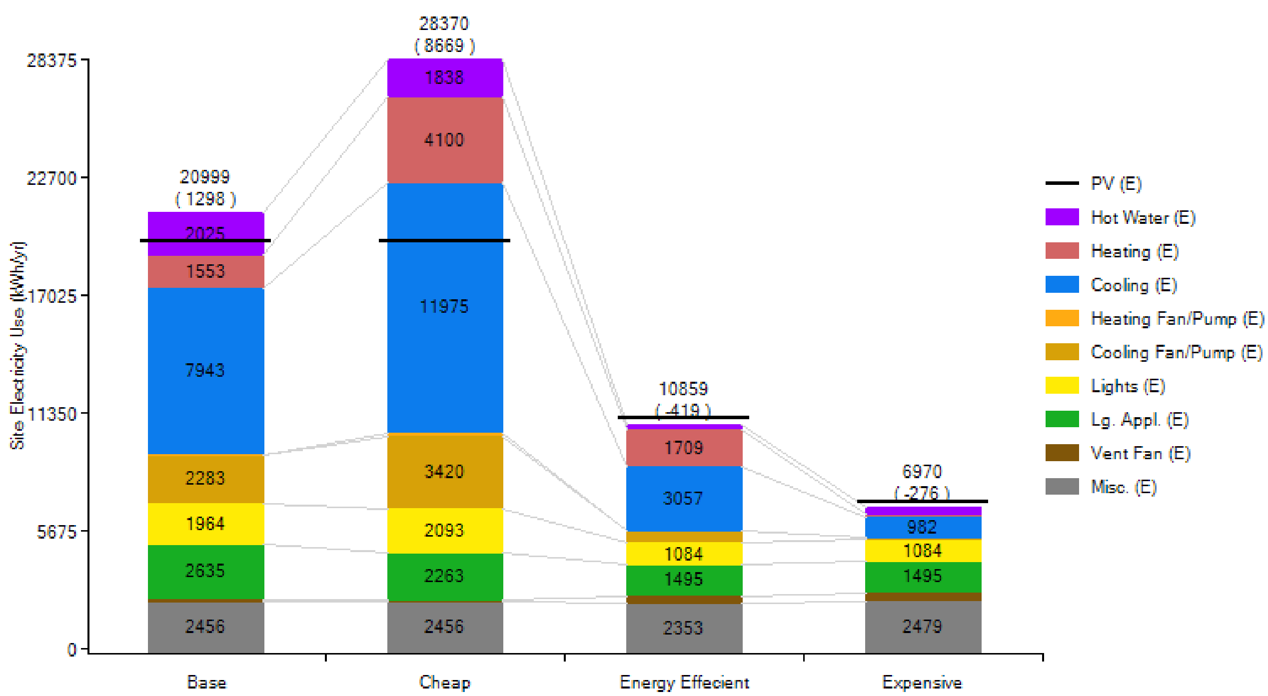

Figure 5. Energy consumption for the four cases in Phoenix, Arizona. This bar graph shows how much energy is consumed yearly by each system in the home. The black line represents the solar energy produced by the Photovoltaic System.

other cities, with 19,700 kWh/yr., the energy used for the cooling systems in both the Base and Cheap cases was too great to reach net-zero consumption.

In Chicago, Illinois, no case was able to make the net-zero benchmark (Figure 6). Chicago becomes far too cold to produce enough on-site energy to reach net-zero consumption, regardless of the level of insulation. Chicago also produced the least amount of solar power for the locations used in this study, at 15,000 kWh/yr. This makes Chicago the most unfeasible locale for net-zero energy consumption in this study.

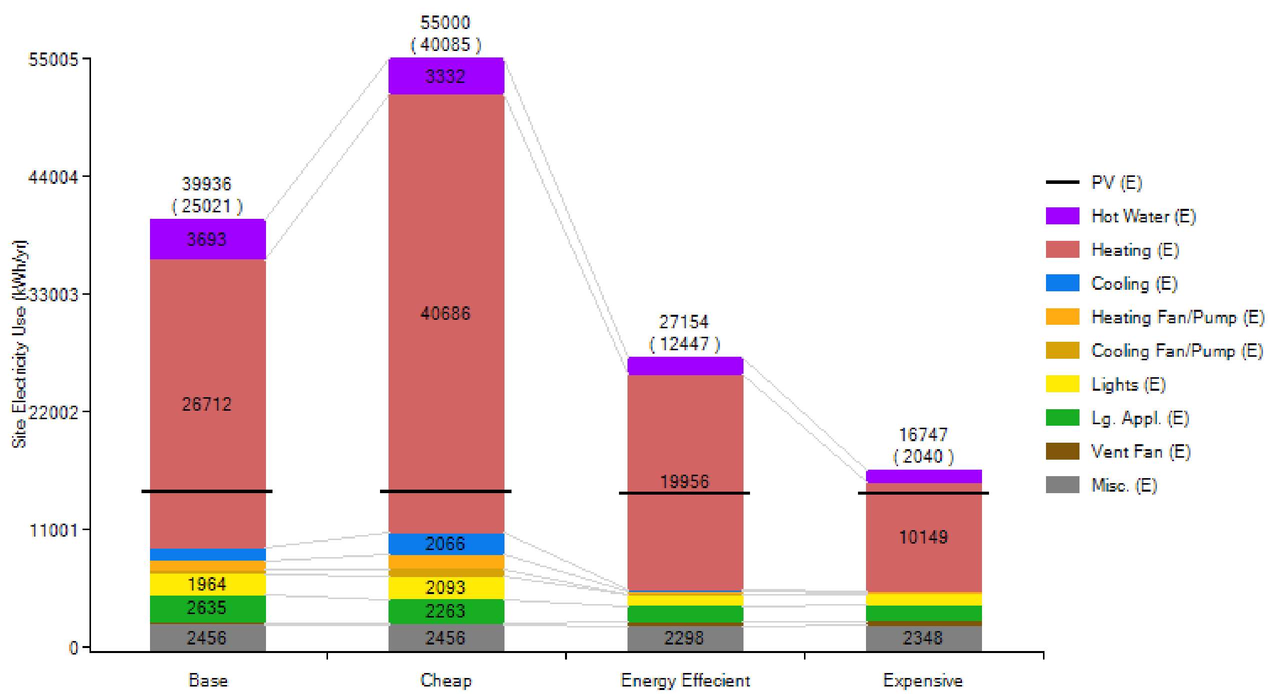

Figure 6. Energy consumption for the four cases in Chicago, Illinois. This bar graph shows how much energy is consumed yearly by each system in the home. The black line represents the solar energy produced by the Photovoltaic System.

In Los Angeles, California, each of the four cases were able to make the net-zero benchmark (Figure 7). Los Angeles has a climate that does not put high demands on either the heating or cooling systems in a home. The solar panels at the Los Angeles location provides 17,500 kWh/yr., which is more than enough to meet the energy demands of each case.

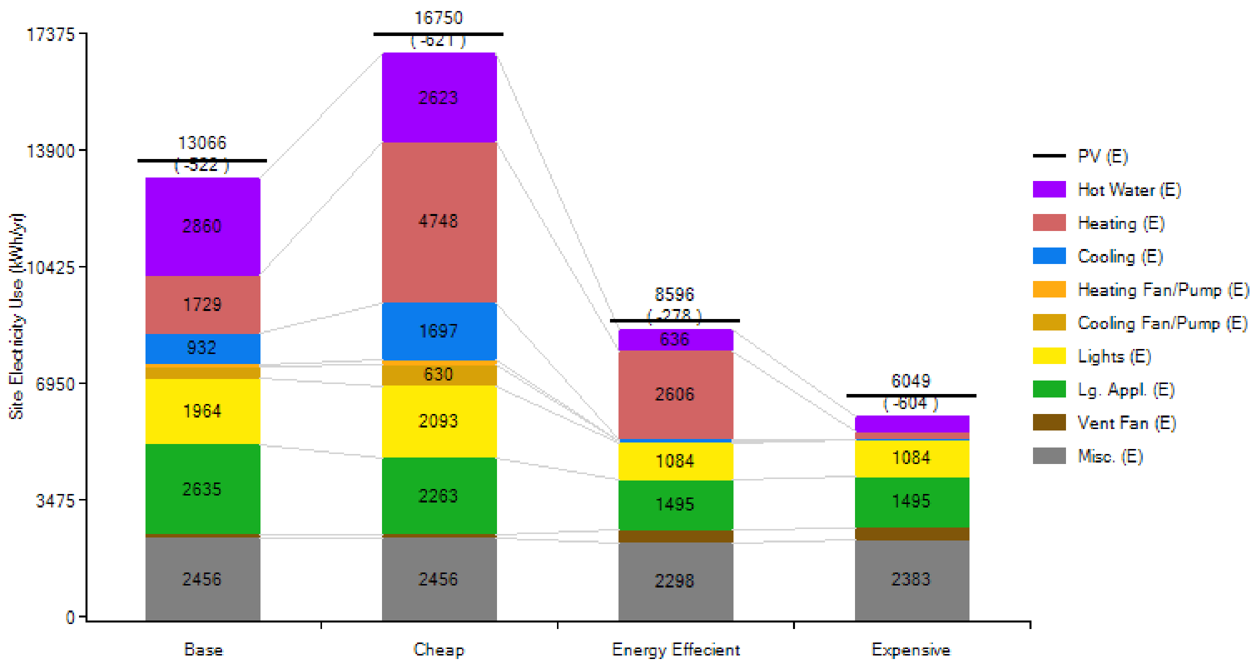

Figure 7. Energy consumption for the four cases in Los Angeles, California. This bar graph shows how much energy is consumed yearly by each system in the home. The black line represents the solar energy produced by the Photovoltaic System.

The impact that the location has on energy requirements of a home is palpable. Both very hot and very cold climates provide difficulties for reaching net-zero consumption. They increase the amount of work needed to be done by the conditioning systems in a home. While the hot climate of Phoenix provided enough solar energy to reach net-zero for the most efficient cases, the cold climate of Chicago required too much energy for the solar panel system to produce enough energy.

The climate of California lends itself to making net-zero consumption feasible. Wheeler and Segar (2012) studied the development of "a new ecological neighborhood for 4,200 students, faculty, and staff of the University of

California, Davis… the project includes housing, commercial space, recreational facilities, and a new community college center on 130 acres" (p. 145). To produce a large-scale net-zero facility such as the Davis project, location played an essential role. Wheeler and Segar (2012) found that Davis, California provided adequate levels of solar power while benefiting from a cooling effect from coastal breezes. For similar reasons, the four cases performed very well in the Los Angeles area. Since the heating and cooling of a building play such an important factor in its energy demands, location can make or break the success of an energy efficiency project.

Sequestering Carbon

Regardless of the energy efficiency of a home, a building will have carbon emissions if it uses energy. For the home to be truly carbon neutral, those carbon emissions need to be compensated for. While various actions will emit carbon, Maiti and Rodriguez (2015) found that there are also activities that can absorb carbon back out of the atmosphere, they discovered that "carbon sequestration is the process of capturing CO_2 from the atmosphere derived from various anthropogenic (human) activities" (p. 1). Of the types of carbon sequestration, terrestrial sequestration is the simplest to do on the type of small scale that encompasses this project. Terrestrial sequestration is the process of planting trees, shrubs or various plants to absorb carbon dioxide from the atmosphere.

Trees have been used in various carbon sequestration projects around the world. A New Zealand university opted to analyze the carbon impact that the trees on their campus had; the trees had been planted some years before as a purely aesthetic initiative. Villiers (2014) found that "4,139 campus trees currently contain 5,809 metric tons of CO_2… estimating that the CO_2 sequestration over the next ten years to be 253 metric tons per year" (p.162). This means that on average, each tree on the campus would sequester an average of 135 pounds of CO_2 per year.

The type and number of tree needed to provide a specific amount of carbon sequestration can be calculated. The United States Department of Energy

[DOE] (1998) produced "a method for calculating the amount of carbon sequestered by trees planted individually in urban and suburban settings" (p. 1). This method, combined with the data from BEopt™, can provide an accurate estimation for a number and type of seedling to plant. To make this project successfully carbon neutral, enough trees need to be planted to sequester a minimum of 4.2 metric tons of carbon a year (Table 3). To sequester enough CO_2 to make the case with the largest carbon footprint neutral, 38.2 metric tons must be sequestered per year.

Table 2
CO_2 Emissions per Year
(metric tons)

	Expensive	**Energy Efficient**	**Base**	**Cheap**
Los Angeles	4.2	6.0	9.1	11.0
Arizona	4.8	7.5	14.6	19.7
Chicago	11.6	18.9	27.7	38.2

This project aims to use a single acre of land for carbon sequestration. The South Carolina Forest Commission (2010) gives recommended spacing patterns for two functions of tree planting: reforestation and wildlife enhancement. The recommended spacing pattern for a single acre of land ranges from 15′ x 15′ for the furthest spaced trees and 6′ x 10′ for the trees spaced most closely together. This respectively results in anywhere from 194 to 726 seedlings being planted in each acre.

Using the DOE (1998) method, calculations for multiple different species of two types of trees are given: conifer and hardwood. The varied species were broken into three types of growth rates: slow, moderate, and fast. Each growth rate was given a survival factor for each year in the lifespan of the trees planted up to sixty years. Hardwood trees generally sequester more carbon than conifer trees, but can take much longer to mature and are more expensive to plant. Conifer trees are fully matured at 25 years; at this year in their lifecycle, the surviving trees of an acre of 194 conifer trees with fast growth rate would sequester 5.7 metric tons of CO_2 a year. An acre of 726 conifers would sequester 21.3 metric tons of CO_2 a year. For hardwoods with the same growth rate in the same timeline, 194 trees would sequester 7.3 metric tons of CO_2 a year, while 726 hardwood trees would sequester 27.3 metric tons of CO_2 a year. This means that by planting a sole acre of either conifer or hardwood trees, or a combination of the two, nearly every case in this project can be made carbon neutral. The only two cases that would need more trees than can be planted in a single acre are the Base and Cheap cases in Chicago. With only two cases failing to meet the carbon neutral goal, that gives the cases in this project an 83.3% pass rate for carbon neutrality. This is a more successful rate than the percentage of the cases that could reach net-zero energy consumption, which were 66.7% of cases.

Projects that are carbon neutral but cannot reach net-zero consumption levels is common. When analyzing the energy efficiency of the Aldo Leopold

Legacy Center in Wisconsin, Utzinger and Swenson (2012) found that "while the building fell short of achieving net zero based on energy balance, better than carbon neutrality was achieved for the Foundation's activities" (p. 165). The reason for this discrepancy is the simplicity associated with sequestering carbon compared to the complexity involved in energy efficient construction. Boyd (2010) describes using terrestrial sequestration "as a viable option in terms of cost and risk" (p. 743). The number of trees needed to sequester a specific amount of carbon can be calculated, and the implementation of that plan can be done with relatively little room for error. While, according to Larsen (2012), "green development projects are generally longer, due to the extended planning processes necessary for innovation at the systems level. The funding strategies for green development tend to be more complex and the financial viability of on-site, clean energy production is still largely dependent on public subsidies" (p. 171). Carbon neutrality being reached through the implementation of terrestrial sequestration is often feasible when net-zero energy consumption is not.

Selecting the Final Design

When selecting the most desirable option, several principles can be considered based on the main goal of the project, three of which are as follow: a design that meets PHI standards, while also having net-zero energy consumption and carbon neutrality. While these goals are important, every project has another extremely important component that impacts appeal of the choices: cost. The case and location that will be chosen for this case study will be the one that fulfills the performance requirements of the overall goal, and has the cheapest material cost.

Of the twelve cases analyzed in this project, five of the cases meet the main criteria for the design: the PHI standard, net-zero energy consumption and carbon neutrality with one acre of tree planting (Table 3). The cases that meet the requirements are the Base, Energy Efficient, and Expensive cases in Los Angeles, as well as the Energy Efficient and Expensive cases in Phoenix. The most feasible case to use as a design is the Base case in Los Angeles.

Los Angeles's Base case is the most feasible for two reasons. The first reason is the cost. The cost of the trees needed for carbon sequestration was inconsequential in the overall material budget, Crawford County Conservation (2015) quoted the average price for the planting of a single tree in an acre-sized plots of conifers as being fifty-two cents; this means that even though the L.A. Base case needed the most trees planted of the five qualifying cases, the extra

Table 3 Design Goal Results					
	Energy Consumed (kWh/m^2 per year)*	**Net-zero energy consumption?**	**CO_2 Emitted (Metric Tons per year)**	**Conifer Trees needed for carbon neutral**	**Material cost*****
LA Cheap	78.5	Yes	11.0	376	$78,494
LA Base	60.9	Yes	9.1	311	$83,141
LA En. Eff.	40.3	Yes	6.0	205	$86,359
LA Expensive	28.4	Yes	4.2	144	$114,420
AZ Cheap	133.0	No	19.7	673	$84,320
AZ Base	98.4	No	14.6	499	$92,396
AZ En. Eff.	50.9	Yes	7.5	257	$90,066
AZ Expensive	32.7	Yes	4.8	164	$114,935
CHI Cheap	257.8	No	38.2	1305	$86,638
CHI Base	187.2	No	27.7	946	$91,975
CHI En. Eff.	127.3	No	18.9	645	$100,412
CHI Expensive	78.5	No	11.6	403	$131,202

***Notes*. *PHI Low-Energy standard = 65kWh/m^2 per year**
**** 726 trees are maximum for 1 acre**
***** Cost of tree planting included**

cost of the trees totaled less than one-hundred dollars more than the alternatives. The L.A. Base case is the cheapest qualifying case because it is designed with typical materials instead of specifically energy efficient materials.

The second reason that the L.A. Base case is the most feasible is because of its constructability. Because this case is designed with standard materials, the contractors would be very familiar with the process of building the home. This would result in the L.A. Base case being built more quickly and with fewer mistakes than energy efficient alternatives, resulting in even lower overall construction costs compared to the alternatives.

Conclusion

The environmental impact that the human way of life has on the world has become apparent in the way that our energy systems discharge pollutants. Organizations have worked to put systems in place to incentivize and set standards for energy efficient construction. These standards have been applied to various projects of all sizes in the past several decades.

This case study shows that environmentally friendly residential construction is a feasible endeavor in the United States. While there are climates in the states that get too cold to affordably lower much of the energy requirements to ideal levels, net-zero energy consumption and carbon neutrality are possible within the right climates. California represents the most feasible climate to apply energy efficient housing standards in. Compared to other climates, there are areas in California that provide such little demand on the conditioning system of a home that a typical home can meet the Low-Energy standard established by the PHI without implementing extra energy efficient measures.

Outside of the climates in which net-zero energy consumption and low energy standards can be met, carbon neutrality can still be possible. Terrestrial sequestration provides people with the opportunity to compensate for their carbon footprint. Planting trees is an affordable step to mitigate the environmental impact that residential buildings in extreme climates have.

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