Zero Energy Homes: A Comprehensive Project-Based Learning Experience for 21st Century First-Year Engineering Students

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***Abstract* - First-year design projects are a special challenge when they include students from many different disciplines. On top of that, there are many skills and abilities that first-year students should learn and experience, including designing (and its various steps), drawing, speaking, creating, teaming, experimenting, costing, analyzing, and caring for the future. Conceptually designing a Net Zero Energy Home (NZEH) provides all of these opportunities, and has elements relevant to all majors. Since first being used in 2010, major improvements have been made that focus on 1) balancing team and individual work so that all students learn the important concepts, 2) increasing active learning, 3) increasing and enhancing experimentation, and 4) understanding the relevance to sustainability. The hypothetical client is a low-income family of four with a limited budget. This results in house designs with about 1,200 ft^2 of floor space. This paper is an overview of the new elements of the project along with insights gleaned from all of our experiences since its inception. The resources described are available for use and adaptation by any interested faculty.**

Index Terms – Design education, First-year engineering, Project-based learning, Sustainability.

BACKGROUND

In 2008, the Pennsylvania Department of Environmental Protection sponsored a project to develop a Zero-Energy Home curriculum for middle school students. After completing that project in 2009, we realized that a similar project would be an excellent experience for first-year engineering students. The project was piloted by Prof. Lau in spring semester 2010, and since then four other faculty at Penn State, and several at other institutions have used it. The project was first reported at ASEE in 2011 [1].

In 2012, a major improvement was made to the spreadsheet-based design tool. Construction costs were incorporated and students were challenged to design a low-cost, affordable ZEH. This was reported on at ASEE in 2013 [2]. Details about the first-year design course and the many aspects of the project can be found in those two papers.

For the last several years, the four co-authors have been using the project each semester, and making some further improvements that improve the overall learning. These improvements are the subject of this paper. This is useful for two reasons. One is greater utility of the project curriculum for students. Two, and perhaps more important to educators, is the reflection and assessment that led to the changes.

OVERVIEW OF THE PROJECT

In its most complete form, the ZEH project is the context for almost everything that occurs in the first half of the semester. The idea is an immersive project-based learning environment on a technology or system that is relevant to young engineering students regardless of their major. The choice of a ZEH also reflects interest in appealing to students across gender, race, ethnicity, economic status, - you name it. We all have lived in some sort of house. And since shelter is a fundamental human need, it also lends itself to introducing sustainability.

Figures 1 and 2 illustrate the various activities that students complete as the project progresses. The activities that flow from left to right are separated into individual ones, near the top, and team-based, near the bottom. Shaded items are turned in for assessment and grading. A grading assistant is essential.

Even though in its complete form, the ZEH project is the basis and context for an entire first half of a semester, it can be modified to be shorter or be used along with other curricula. Only one of us uses it as the entire first half-semester context.

The in-class time of six hours per week is taught more like a studio, with learning via activities and application of new principles and concepts. Here our guiding idea is "learning by doing." Some of the changes have been to eliminate or reduce analytical work on paper, and instead to use more interactive design tools, and more teamwork. By focusing on the thinking of how to use and interpret the information from tools, students are learning at a higher level than is typical with calculation-intensive work.

As you can see from the figures, there are many different kinds of activities, involving tools and techniques like spreadsheets, graphs, sketching, parameter sensitivity,

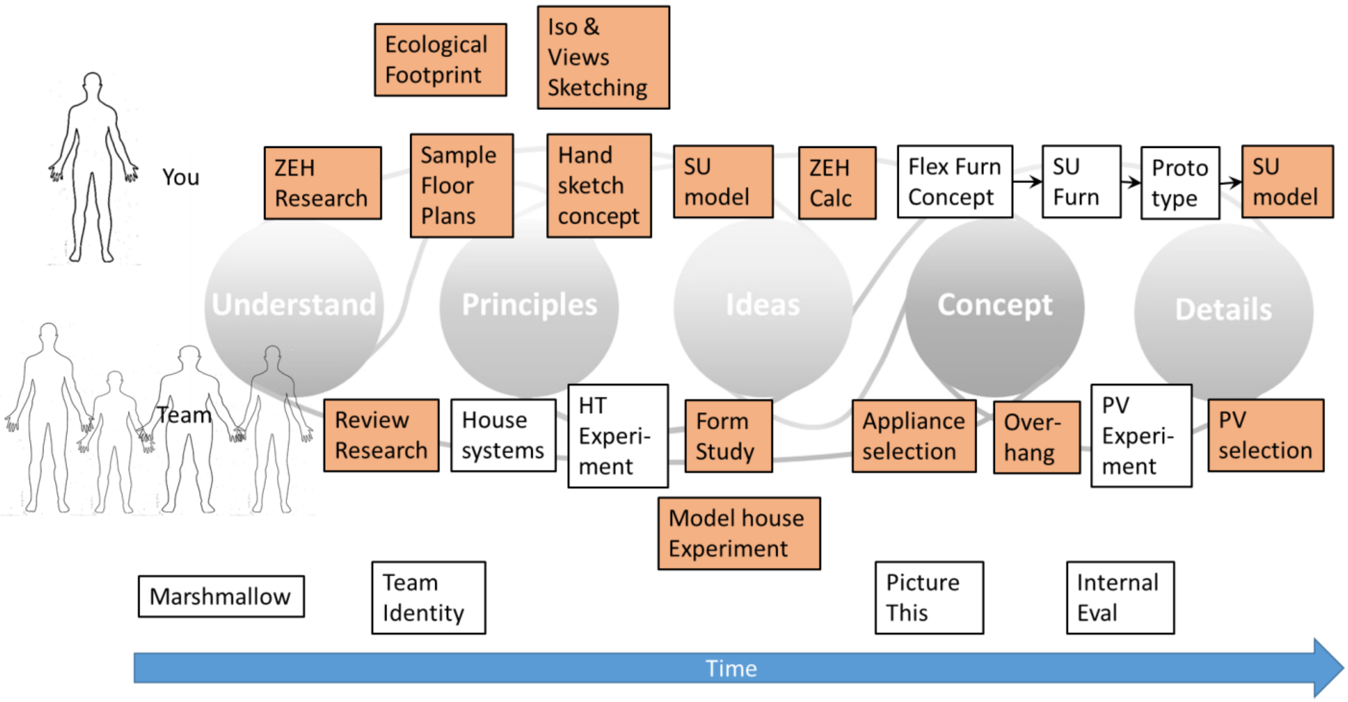

FIGURE 1
ACTIVITIES AND ASSIGNMENTS FOR INDIVIDUALS AND TEAMS DURING FIRST PART OF ZEH PROJECT.

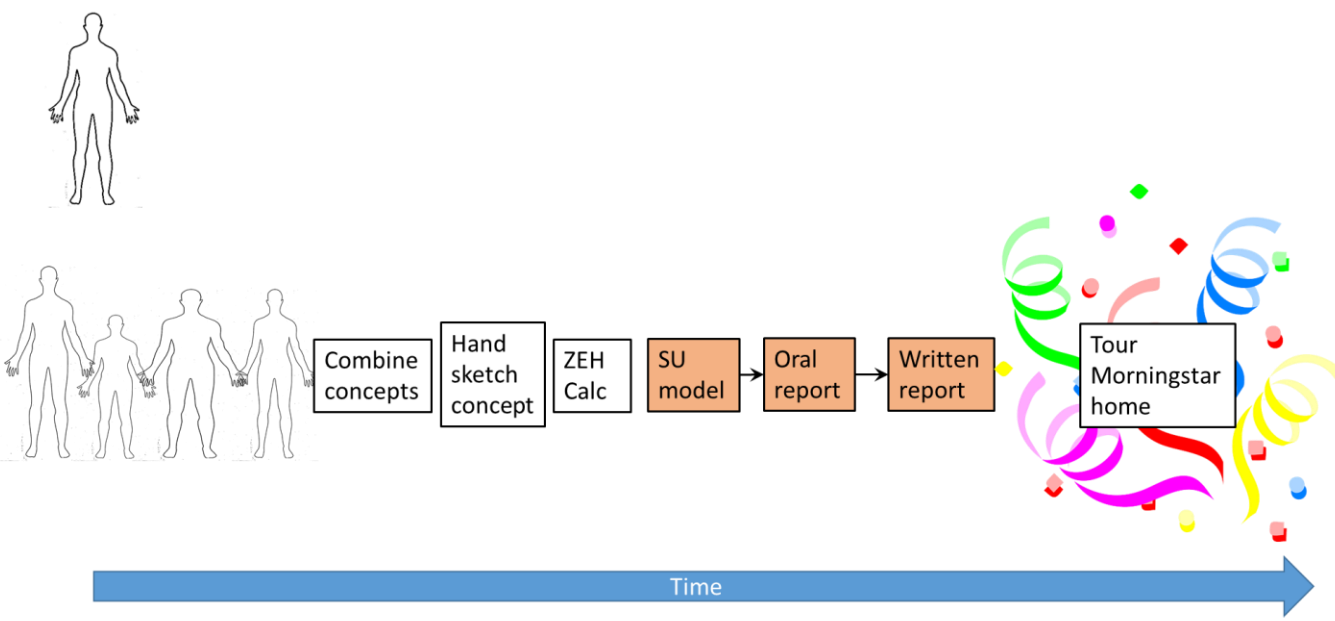

FIGURE 2
ACTIVITIES AND ASSIGNMENTS FOR INDIVIDUALS AND TEAMS DURING LAST PART OF ZEH PROJECT.

experimentation, research, reporting, 3D drawing, cost-effectiveness, systems thinking, and innovation.

LEARNING DESIGN: SEEING, INTEGRATING, DEDUCING

One common fundamental lesson when learning about passive solar energy and building design is understanding the apparent movement of the sun in the sky. The daily and seasonal variation can be used to improve the use of solar energy for heating. A relevant application for a ZEH house is the design of the roof overhang length on the south wall.

In previous semesters, students began learning about solar energy with a carefully prepared interactive slide show intended to have them learn essential principles about solar energy. These principles included:

1. Power is the rate of energy transfer.
2. Solar energy is spread out.
    a. Maximum power is about 1 kW/m^2.
    b. Average daily energy is about 4 kwh/m^2 in the Northeast; data is available by month and location.
3. Solar position at any time can be determined and is mapped with a sun path diagram (see Figure 3).
4. Solar features do not have to face due south nor be tilted at the "optimum" angle. The NE climate is partly cloudy, and much of the solar energy comes from the sky and from reflection from the ground.
5. Long-term solar energy savings can be estimated using the concept of efficiency and solar energy data.

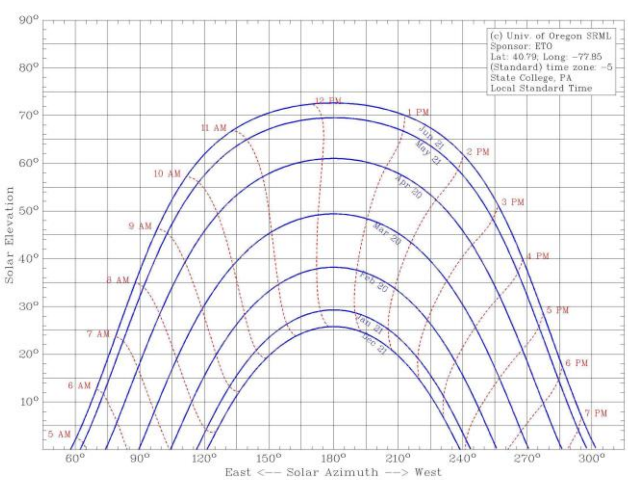

FIGURE 3
SUN PATH DIAGRAM FOR STATE COLLEGE, PA.

As the slides were presented, there were simple problems that were done to demonstrate how these principles might be useful. They were mostly problems that were out-of-context with the immediate needs of designing a ZEH, e.g., use the sun path diagram to find the length of a flag pole shadow at a specific time of day and year. It's not that the principles and the connected problems weren't well thought out; they reflected 40 years of experience in solar engineering. And they also reflected the way that we learned as students: introduction of new material followed by stand-alone application of the concepts via homework.

The homework set that was completed individually, outside of class, had several independent problems, ending with some insight into how an overhang over a south-facing window can work in concert with sun angles and the need for heating. Students have always struggled with this homework.

Upon reflection on this unit, it became apparent that students were struggling a lot with the analytical type problems they were asked to solve. Not only that, they were getting lost in the details, worrying more about how to adjust for Daylight Savings Time when using a Sun Path Diagram, than how to use the solar dynamics to design a high-performance house. When asked to reflect on what they learned about overhangs, they often missed the connection to heating and cooling.

And perhaps worst of all, the in-class learning was too disengaged from their project. Furthermore, it introduced a complicated new tool – the sun path diagram. We suspect that there is another thing happening with the chart. Students are no longer accustomed to using static graphical tools like this. One can easily find solar angles and all kinds of other information using the internet. While we can rationalize about why the chart is important, it may not be needed and can detract from more important higher-level learning.

A new approach was needed.

This semester, a fresh approach was used. No more sun charts. No more solar principles slide show. Instead, a simple model of a house was shared in SketchUp, see Figure 4, and used as the basis for each team to investigate how the overhang length affects shadows and how they change with time of day and time of year. In SketchUp, the designer can model the movement of shadows just as they would appear in the real house. A simple tool has sliders for time of year, and for time of day.

One integrative feature of this approach is that students are already familiar with SketchUp from earlier practice sketching a home concept. The learning, instead of figuring out how the shadows are determined, now focuses on insights into the interplay of overhang length and shadows.

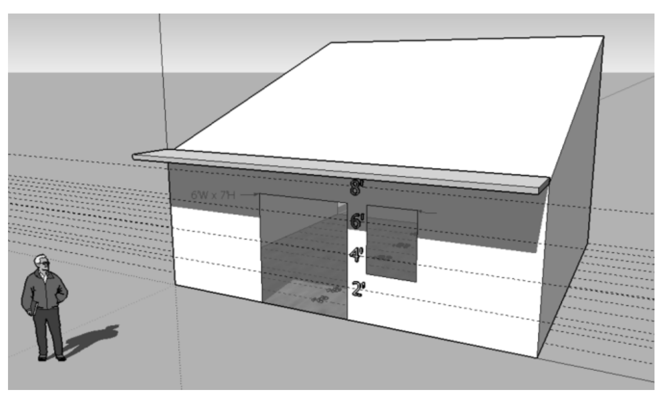

FIGURE 4
SKETCHUP MODEL USED TO STUDY OVERHANG SHADING.

Seeing the shadows change on the wall and windows of a house, albeit a virtual one, as one chooses different overhang lengths and different times of day and different times of year focuses attention on the situation at hand.

Rather than just generating a single number with little relevance, this problem requires students to think about what their design is trying to achieve. By "playing around" with the dynamics of the shadow and its relation to time of year and day, students observe that shadows can be long in summer and short in winter. They can also see how the light penetrates deep into the space in winter, even with an overhang. But just how long should the overhang be?

Too long and it shades in months when heat is needed, and the sunlight can contribute to heating. Too short, and there is little shade in warm months when shading is desired.

Then a further complexity was added to the investigation – months with similar shading, e.g. March and September, can have different needs for heating and cooling. If an overhang is long enough to provide a lot of shade in September when it is still warm outside, it will also shade in March when heat is needed from the sun.

Discussion ensued within teams as to just what it is they can systematically study with the SketchUp model. The model allows the shadow length to be estimated, and from that the fraction of shading can be determined for the tall and short windows. Then a question is what times should be investigated. Most settled on a few months spanning the seasons, and one or two times of day. Finally, when the shading variation is tabulated, a decision must be made that trades off the desire for summer shading with the desire for winter illumination. Some recognize that added shading can be applied using blinds or curtains, but if more light is desired, nothing can be done about the overhang shadow.

This type of problem not only gets students involved in discussion and negotiation, it also requires making tradeoffs and reasoning about how to make a design decision. Teams write up a two-page report on how they designed the overhang length. This provides further opportunity for all of the team members to reflect on what they just did, and what they learned.

Another way that this project-based learning develops students design abilities is its tendency to lead to the use of tools as a supplement to design thinking. As the project involves several pieces of data, it leads to analysis with as spreadsheet. Students have used these before in the project to do a parametric study, and to collect and refine experimental results.

PRACTICING DESIGN: HANDS-ON EXPERIMENT IN PASSIVE SOLAR

One of us, Bharti, emphasizes principles of passive solar heating and cooling. Students are introduced to passive solar features during the first week of class. They practice implementing these features on a standard home. This is followed by a visit to the Penn State's Morningstar home. This building was the fourth place finisher in the 2007 Solar Decathlon competition, and demonstrates the state-of-the-art of energy-efficient home design. It includes an 8.3 kW solar array, evacuated-tube solar water heating, structural-insulated-panels (SIPs), natural lighting, green materials, ground-source heat pump, energy-recovery ventilator, and high-efficiency appliances. The field trip to the Morningstar home provides a practical demonstration of their theoretical knowledge on passive gain as well as some new ideas on active solar.

Students are then assigned their design challenge wherein they must design and build a 70 square inches passive solar home[1] using the following materials:

- 32" x 20", 1/8" thick foam core board
- 1 sq ft thin clear plastic wrap
- 4 sq ft Aluminum Foil
- 2 sq ft thin rubber
- 2 sq ft black fabric
- Hot glue and/or tacky glue
- Thumbtacks
- Scotch tape
- Masking tape

Prior to the start of the project there is an in-class discussion on how each material can be best used to implement passive solar gain. The students must also be able to remove the roof of their house so that they can demonstrate their designs of the internal layout of the house. The intent of the internal design is to attempt to place rooms in a way that best utilizes their solar gain.

The class hour prior to their Zero Energy home presentation is spent on experimenting on their houses. A 250 Watt lamp and a box fan is set up to imitate sun and an easterly wind respectively as shown in Figure 5.

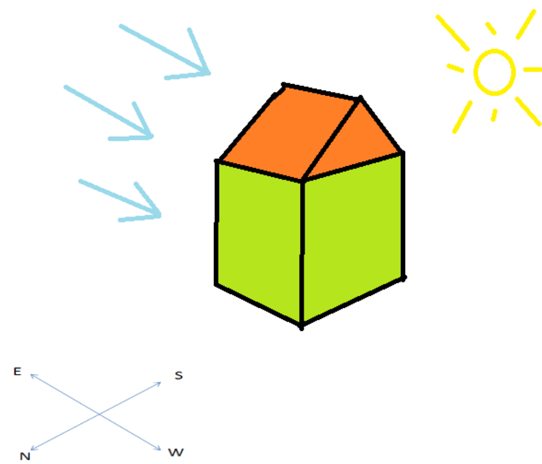

FIGURE 5
EXPERIMENTAL SETUP FOR ZEH PASSIVE SOLAR EXPERIMENT.

The house is first subjected to the lamp placed 8 inches away from the home. Students record the effect of the simulated solar gain inside their house by measuring inside temperature with a thermometer (shielded from the light). After recording temperature for about 20 to 30 minutes, the lamp is then switched off to simulate night and the house is subjected to an easterly wind using the box fan placed a couple of feet away from the house. This part of the experiment takes about 10 to 20 minutes. Students record temperature inside the house every minute. The results are plotted and students are encouraged to look at other designs in their class and talk about what they could have done for better results.

Some important insights emerge from these experiments. One is that air leakage matters a lot. The better sealed model houses heated up to a higher temperature and cooled down less. Students who are intrigued may go on to do Tech Time (see later discussion) research on Energy Recovery Ventilators. Another lesson is the trade-off between lots of glass for allowing sun in, but then also losing heat faster at night. Maybe the most important insight is that solar and light energy can heat a home.

KEEPING EVERYONE ENGAGED: INDIVIDUAL AND TEAM WORK

Students are in teams of four. A constant challenge is how to manage team-based projects so that every one learns to their fullest advantage, and is assessed in a fair and just way. One gradual shift has been to have more individual assignments and slightly less group assignments. This helps to hold students accountable and leads to better team performance. Many of the individual assignments contribute to a following team effort. On the down side, it means more time grading the assignments. A grading assistant is highly recommended.

One module added this past semester is the design of a multi-function piece of furniture. This not only provides an opportunity for individual achievement, it creates a product that is used in their ZEH concepts. It is also a microcosm of the larger ZEH design project, and a different context to apply a design process.

Teams start with listing functions in each of the major rooms in the house: kitchen/dining, living, and bedroom. They then brainstorm all possible combinations of functions, gradually narrowing it down to four, multi-function furniture concepts. Then each team member takes one of the four to further develop.

After some brief searching on-line for similar concepts, students hand sketch their concept, with the intent to create a 1/8 scale prototype in the workshop using cardboard, glue, and miscellaneous materials. The prototype is meant for them to show the functions and positions of their concept. It is important for them to make appropriate sketches, with some dimensions, prior to entering the shop.

Then they get about an hour of shop time to produce a prototype. Following this they make a one-minute presentation about their concept. The entire class is encouraged to ask questions and make suggestions for improvement. Students are encouraged to incorporate good suggestions into the next iteration of their design concept.

The next class meeting each student makes a SketchUp model of their design and uploads it to the SketchUp 3D Warehouse, a database of user-created models. The furniture must be detailed and shown in all functional positions. It must also include a paragraph explaining the furniture and its functions and features. This provides a sense of closure, as well as a sense of contributing to the design community. These models are then assessed for a grade.

This four-hour project further reinforces designing as a process, from ideation, through sketching, protoyping, redesigning, and detailing. It is a chance for each student to apply the process, while being immersed as a team within a larger and longer project of conceiving a ZEH.

Three other individual assignments have been added all involving an individual's student's own design concept for a ZEH. They start by hand sketching a concept, including floor plans and elevations. This gives practice with classic 2D drawing techniques, including drawing to scale. These sketches are copied and turned in for evaluation. Then each student draws their house concept in SketchUp. Everyone achieves some basic functionality with this general-purpose 3D drawing program. These models are submitted for evaluation. Finally, each student applies the ZEH Calculator analysis tool to their design. They are given an assignment that methodically leads them through design options while they track the impact on cost and solar array size. A brief report is submitted summarizing what they learned by using the tool.

KEEPING EVERYONE ENGAGED: DESIGN ACROSS DISCIPLINES

Because this class is taken by nearly all engineering disciplines, we look for ways to teach design that are not so discipline-specific. One of the biggest challenges for first-year design courses is to be useful and relevant to any engineering student, regardless of their major. In our case, we have students from all engineering majors in the college, except architectural and computer.

That is one of the greatest aspects of this project. It does not represent any one discipline, and a home is a rich context that has relevance to all disciplines. Not only that, it is a context that first-year students have some experience with.

Nonetheless, it is still challenging to relate well to Chemical Engineering in this project. If you're interested in electronics, there's not a lot here. Recognizing this, another element was added to this project – Tech Time.

Tech Time is a team-based project to investigate some aspect of technology relevant to ZEH's, and to provide a 15-minute presentation to the class to tell us what they learned that might be useful for the projects. For this effort, students are put in different teams that are organized by majors. The idea is that this is a chance to work on something more relevant to their disciplines and interests.

What do the Chemical Engineers do? They might investigate Living Machines, an ecological method of treating sewage. They look at grey water, and rain water. recycling and treatment. Electrical engineers might look at smart appliances, or induction ranges. A suggested list is provided, but teams are encouraged to propose their own ideas.

There's a lot to be said for Tech Time. It contributes to an atmosphere of working together, both among the teams, and between students and faculty. They often have ideas that are picked up on by teams and incorporated into their designs.

On the other hand, it takes about one week of class (6 hours in class, 2 hours outside) to do a round of Tech Time. Some of us do two rounds in a semester, using a second round for the industry-sponsored project during the latter half of each semester.

Another approach we've tried to address all disciplines is to develop modules that are discipline-focused. The biggest challenge here is to integrate the module into the curriculum, a special challenge for project-based learning. We much prefer the Tech Time approach to satisfy the need for discipline-focused topics and learning.

SUSTAINABILITY: MORE THAN JUST TECHNOLOGY

We all recognize that the ZEH project has value in introducing sustainability, and the role of engineering in that vision. We want students to take away the message that we can all live decent lives within the means and limits of Earth. That involves technology for sure, but it also involves changing our world views.

The first year this project was used, students made a video about their project. One of the teams had the message that sustainability can be achieved without any sacrifice or fundamental change. They claimed that all we need is to cover our roofs with solar electric panels.

This is despite having completed an exercise early in the semester wherein they determine their Ecological Footprint (EF). This is a measure of how much of Earth's bioproductive land and sea area it takes to 1) provide resources, and 2) assimilate wastes. A typical result is that if everyone lived like we do, it would take five Earths. We talk about how we need to reduce our impact by at least a factor of five, and even more to leave room for some growth. That will take a combination of better technologies and reduced consumption. It will require more attention to meeting people's fundamental needs for a decent life.

Considering Nature's limits, and constraints more generally, led to the previous initiative to include costs of the house elements, and then to design for a low-income family with modest financial means [2]. Constraining the design in that way brings in some social justice aspects, as well as forcing the students to be innovative with the smaller house that can be afforded.

When they apply the ZEH Calculator tool to their design and consider all of the design options, they find that behavior, more than any technology, has the greatest positive impact on energy use. One of us goes further and has students do an exercise where they eat vegetarian to consider how to lower one's food impact.

Recently, the rising popularity of TV shows about tiny houses, and paring down possessions, has provided validation and video that can be used in class.

CONCLUSIONS

We use this project because it is a good one. The improvements reported here have made it even better. It has the ability to be a complete half-semester project-based learning experience. Its most outstanding attributes are:

- Relevant technology to all students (and faculty)
- Balances individual and team learning
- Integrates tools and process into project
- Utilizes active hands-on learning
- Includes sustainability both from technology and life-style.

The authors will be glad to share any and all resources associated with this project.

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[4] Author's Last name, First initial, Middle initial, "Title", *Journal or book (italics),* Vol, No #., date, pp.

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