AC 2012-2991: DESIGN OF A ZERO ENERGY HOME AS A FIRST-YEAR DESIGN PROJECT

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Design of a Zero Energy Home as a First Year Design Project

Abstract

This paper describes in detail a novel, first-year, half-semester design project focused on Zero Energy Homes (ZEH's). The project has been used for three semesters and provides a relevant context for learning and applying the design process. Students apply design tools including spreadsheets, system analysis, 3D drawing, model building, research, reporting, and customer needs, all in a team-based active-learning environment. A ZEH is a high-efficiency home that is well-insulated and air-tight, oriented and designed to utilize passive solar heat, and fitted with high efficiency appliances and HVAC systems (heating, ventilating and air-conditioning). A solar thermal water heating system further reduces the energy use. The remaining use of electricity is provided by an integrated solar photovoltaic system and/or an on-site wind turbine. These homes are grid connected and sometimes draw energy from the grid; at other times they put energy into the grid such that on an annual basis, the net energy use is zero. There are several notable features of this project – most significant is that it provides the context for learning design. Students begin by using a visualization team activity for identifying the desirable features they would want in their future homes so that they realize that ZEH's provide what people want while also using zero net energy. System concepts are also emphasized by identifying and analyzing home components and their interconnections. A specially developed spreadsheet tool allows the student designers to see how design choices affect the overall energy use. Sustainability and green design concepts are introduced; students calculate their ecological footprints and research ways to reduce them. Students also learn some engineering concepts like overall heat transfer, thermal resistance, air leakage and its energy cost, and become familiar with technologies including ventilation air heat recovery, solar water heating, heat pump operation including ground-source heat pumps, passive solar heating, and solar electric systems. In the process of choosing certain components, students learn to balance first costs and operating costs, and are introduced to the concept of life cycle cost, cash flow, and financing. Google SketchUp is learned and used to create 3D virtual models of their houses. Students also construct a physical scale model of their home. Through the integration of a real world design challenge and systems thinking, students leave this project with the ability to engage in the design process, solve complex problems, and develop thoughtful solutions.

Background on the course

The Zero Energy Home project is one of two extended half-semester projects that form the basis for the first-year engineering course EDSGN 100, Introduction to Engineering Design. At Penn State, most engineering students must take EDSGN 100, and most take it in their first year. At University Park and the other Penn State campuses, approximately 1800 students complete EDSGN 100 each year.

The course is three credits and meets three times a week for fifteen weeks. Each meeting is for two 50-minute periods which is twice that for a lecture-based course, reflecting the hands-on practicum nature of EDSGN 100. At University Park, our facilities for the course allow for one of the weekly meetings to be in a typical technology classroom with a computer tied to a projector, and flexible seating with tables and chairs that can be moved around. Another class is in a room that has lab benches designed for each team to have a bench and two computers. This room, called the "design lab," also has a main computer with projector, as well as testing and measurement equipment. Adjacent to it is a workshop with woodworking tools that students can use to make prototypes. This workshop also has a rapid prototyper that students can use. The third meeting room is a computer lab with custom-designed tables allowing teams of four students to sit together and each have a computer. This room is mainly used to teach and apply solid-modeling software, but is also used to teach use of spreadsheets, web page design, and other computer-intensive applications.

Over the last three years, the EDSGN 100 faculty have worked on improving the course learning objectives and associated learning outcomes. Currently, our objectives are that students completing the EDSGN 100 course will be able to:

1. Conceptually design a system, component, product, service, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability
2. Participate effectively in small teams,
3. Communicate effectively using written and graphical forms and oral presentations,
4. Demonstrate professional and ethical responsibility
5. Use software tools relevant to engineering practice.

The course has continued to evolve from one that mainly taught students engineering graphics to one that focuses on the engineering design process, with graphics being one of the communication skills supporting the design process. As it is now constructed, the course uses two significant projects as the context for teaching design. The first project ranges from product dissection and redesign to system design, with different faculty choosing and developing their own projects. Of the 30 sections across the university in any semester, there are around a dozen different first projects. The first project is more structured and provides the students with an opportunity to learn and apply a design process while developing their teamwork, communication, and ethics skills. The second project is industry-sponsored and more open-ended, and typically all teams in all sections work on the same project. Students apply stakeholder needs assessment, ideation, research, analysis, testing, concept selection, detailed design, prototyping, and reporting.

Background on Zero Energy Homes

A Zero Energy Home (ZEH) is a high-efficiency home that is well-insulated and relatively air-tight, oriented and designed to utilize passive solar heat, and fitted with high efficiency appliances and HVAC systems (heating, ventilating and air-conditioning). A solar thermal water heating system further reduces the energy use. The remaining use of electricity is provided by an integrated solar photovoltaic system and/or an on-site wind turbine. These homes are grid connected and sometimes draw energy from the grid; at other times they put energy into the grid such that on an annual basis, the net energy use is zero. Typical monthly patterns of production and consumption might look like that in Figure 1.

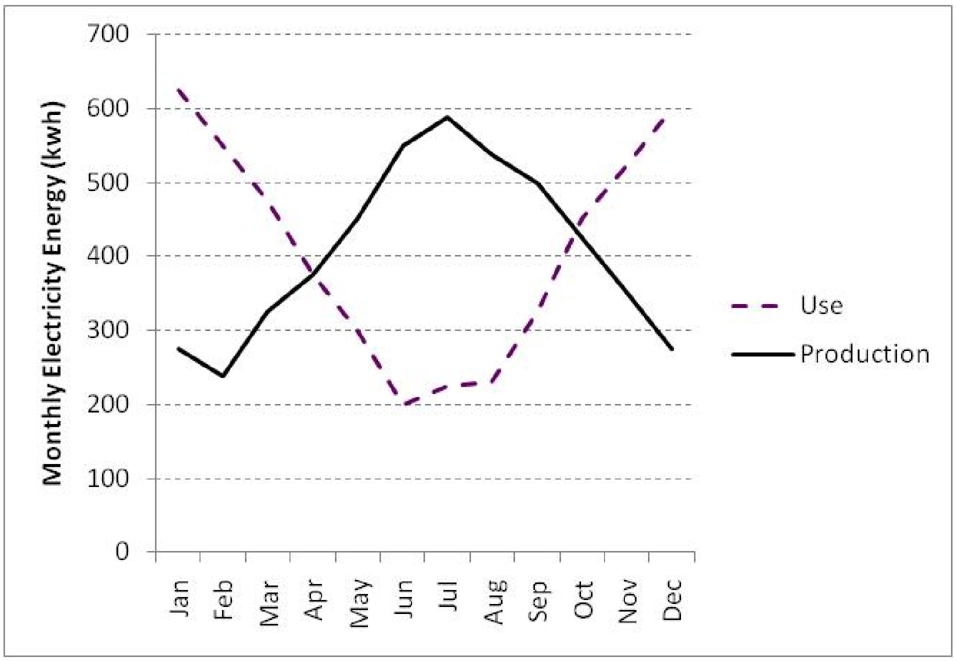

Figure 1 Monthly energy use and production in a ZEH

Project Overview

The Zero Energy Home (ZEH) project evolved from an earlier curriculum development project funded by the Pennsylvania Department of Environmental Protection (DEP). That project was intended for middle and high school teachers and resulted in a four-unit curriculum:

1. Sustainability and Zero Energy Homes
2. How Do Homes Use Energy?
3. Solar Technologies
4. Designing a Zero Energy Home

The inspiration for the DEP project came from Professor Lau's experience working on a ZEH project as a consultant and partner with the 7group, a green building consulting firm. Prof. Lau also has over thirty years of experience designing and studying solar homes.

After the conclusion of the DEP project in 2009, Prof. Lau realized that much of the engineering principles and the ZEH context could be adapted to serve as the first design project in EDSGN 100. The project was piloted by Prof. Lau in spring semester 2010, and in fall semester 2010, two other faculty used it in their sections of the course, one of them being Prof. Sulewski. In spring 2011, two additional faculty utilized the project.

The project is intended to take seven to eight weeks to complete. It is also designed to utilize team-based active learning in the classroom. Most importantly, it serves as a rich context for learning and applying engineering design principles and selected analytical concepts, most notably conservation of energy.

A weekly outline of the project topics and activities is shown in Table 1.

Table 1 Weekly outline of topics and activities for the ZEH project.

Weekly Topics	**In-Class Activities**
1 Project introduction Developing a ZEH team vision (customer needs) House systems	Team building exercise Discuss ZEH's Do visualization exercise (note materials needed) Do house systems game (materials) Review ZEH research needs
2 Research on ZEH's ZEH overview ZEH geometry Sustainability & Ecological footprint	Gather ZEH research into a team summary Review general findings – teams Watch webinar and/or use slides on ZEH's in PA to provide overview – complete worksheet Introduce isometric sketching and sketch form study Introduce sustainability and Ecological footprint using slides
3 Solar principles Solar angles Product life cycle Using Google SketchUp Hand sketching	Hand out and review solar energy principles; do sample problems Watch and discuss *Story of Stuff* Use SketchUp to make a basic house Play *Penn State Picture This* Hand sketch elevations and floor plan of house concept
4 Thermal envelope & heat transfer Passive solar design concepts Appliances	Introduce envelope and air leakage Perform heat load experiments with coolers Analyze appliance energy use and cost (with system sketch) Prepare for appliance research
5 Energy principles HVAC systems	Compile appliance research reports Review the various types of HVAC systems with emphasis on efficiency Review the slides on ground-source heat pumps Investigate how house size affects energy performance Do some example delivered energy cost calculations
6 Solar electric Solar thermal Using the ZEH Calculator Building scale models	Explore solar water heating using slides Describe system, components and costs for solar water heating and solar electricity Using the ZEH calculator to analyze house details and to size solar electric system Build scale model of house using chipboard to 1/8"=1'0"

Weekly Topics	**In-Class Activities**
	Build SketchUp model of house with solar features
7 Work on project	Work on physical model, SketchUp model, and oral and written reports
8 Final presentations	Complete physical and CAD models Prepare presentation and report Give oral presentations

All of the supporting materials for this project have been developed with the intent of transmitting the project to other colleagues to use as appropriate. Interested faculty can request these by sending an email to Prof. Lau at asl1@psu.edu.

Highlights

The project has been well received by students and by faculty. There are several notable attributes. Most significant is that the project provides the context for nearly all of the learning objectives during the first half of the course. Rather than a hodgepodge of many seemingly unrelated topics, each new topic is introduced when it is needed for the project.

<u>Form Study</u>

For example, isometric sketching is introduced as a tool in visualizing how a house's geometry affects the potential energy performance. This exercise also presents an opportunity for introducing parametric studies as well as using a spreadsheet for analysis. Figure 2 illustrates the product of the form study that students do in class while the professor steps through the process on a tablet computer with projection. In this case, the total house floor area was held fixed at 2,000 square feet while the rectangular floor profile (L/W) was varied from an aspect ratio of 1 to 3, along with the number of floors varied from 1 to 3. Not only do the students get to practice isometric sketching, they learn about parametric studies. This situation was also used to draw out the fact that the total surface area directly affects heat loss, and therefore the smaller the surface area the better. Additionally, because of the desire to utilize solar energy, the house should have a large south facing surface area.

To supplement the visual feedback, a spreadsheet is developed interactively with the class. This results in a tabular presentation of the parametric variation along with some graphs. Because there are two independent variables, graphing presented an opportunity to teach how to make and interpret 3-D graphs. Figures 3 and 4 illustrate the results.

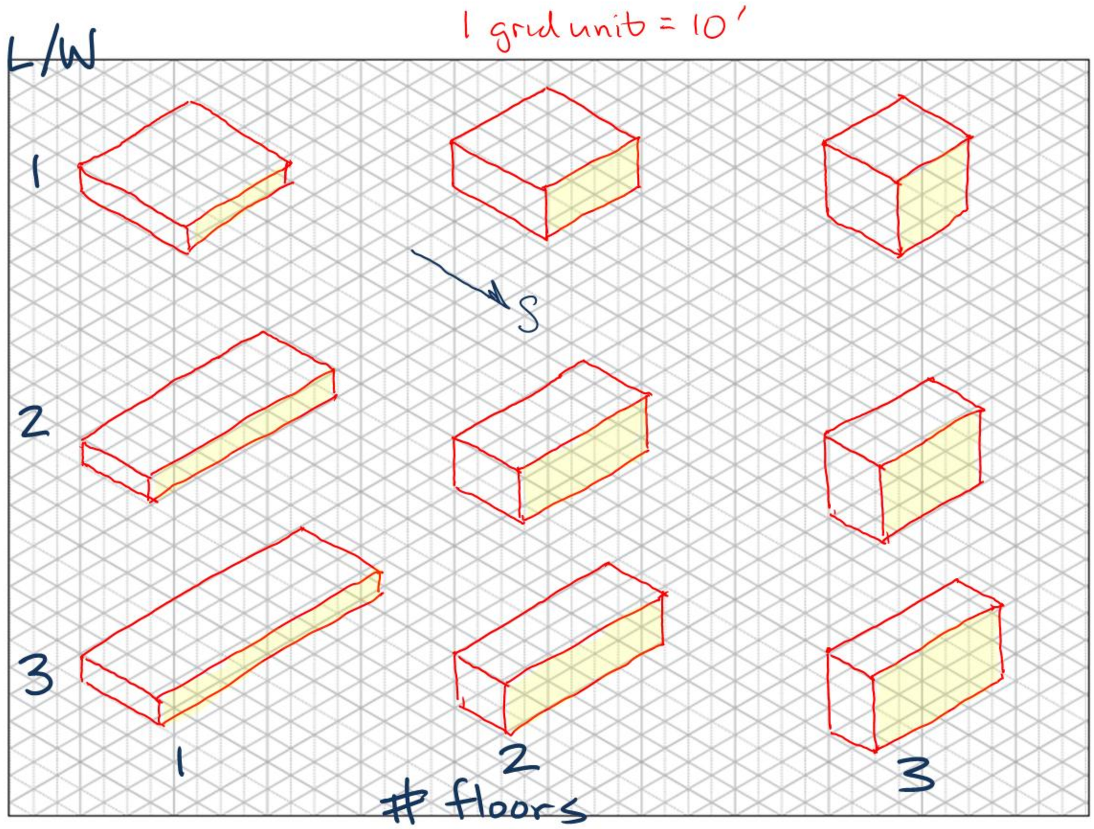

Figure 2 Isometric sketches of house from parametric study

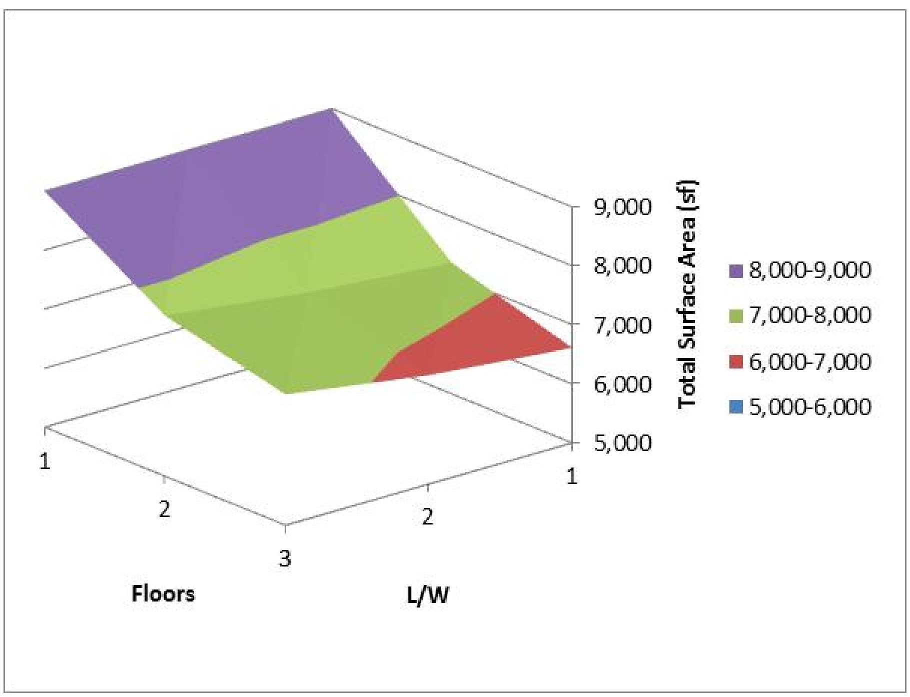

Figure 3 Effect of house form on total surface area

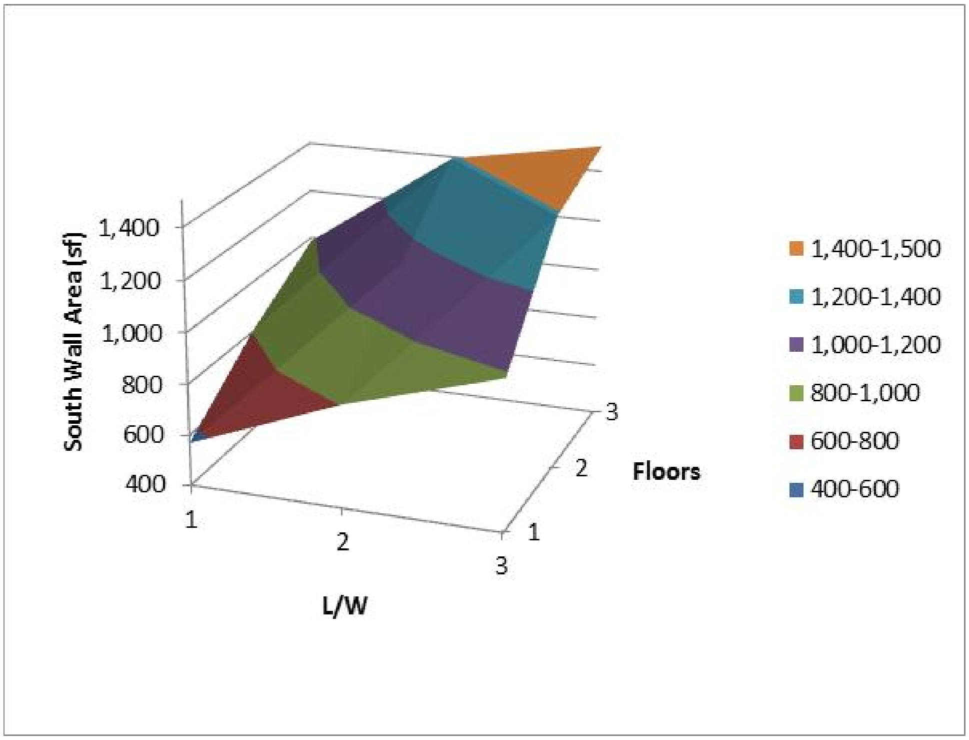

Figure 4 Effect of house form on total south wall area

One relevant observation from Figure 3 is that the total surface area, which we want to keep low to reduce heat loss, is not much affected by the aspect ratio. Number of floors has the most impact going from 1 to 2, with one floor having the most surface area. The minimum surface area is for L/W=1 and three floors. South wall area, which we want more of for passive solar heating, is more sensitive to both parameters as illustrated in Figure 4. As L/W and number of floors increase, the south wall area also increases. Here the maximum is for L/W=3 and three floors. Students recognize that a high aspect ratio is an atypical house form and that the narrowness of the one dimension restricts the interior layout. The most common house type with a large aspect ratio is a townhome or row house. The students final concepts are typically detached, two-story and close to an L/W of 2. So while they learn something about the ideal form for energy use reduction, they also experience that other factors are important too, in this case “normalcy.”

Social Context

In addition to providing the context for achieving the course learning objectives, this project is a real-world example of how engineers contribute to making the world a better place. Before developing the middle school curriculum, Prof. Lau served as an engineering consultant on several energy-efficient house projects including one designed to be net zero energy. Furthermore, Prof. Lau was one of the faculty leaders in the 2007 Penn State Solar Decathlon entry that finished fourth out of twenty schools. This house is now part of the Penn State Center for Sustainability where students can tour the facility. Not only do students learn about how these buildings are designed, they learn about why they are important for future sustainability. This approach of emphasizing the positive social contributions of engineers is consistent with the idea of *Changing the Conversation*[1].

Customer Needs Activity

Students begin the project by using a team process for identifying the desirable features they would want in their future homes. This happens before energy use is even considered leading them to realize ZEH's can provide what people want (customer needs) and use zero net energy. The process begins with a guided visualization where the professor leads students, with eyes closed, to picture their future house paying attention to the features and appearance. They then write each feature they recall on a post-it note. The four-person team then post these notes on the wall and organizes them into groups using whatever organization emerges. This organization step is done silently, requiring students to use creative team communication strategies. Each student then uses a selected number of stickers to vote for the features that are most important to them. They record the results and use these features as part of their design goals for their team house concept. These features generally involve form, function, beauty, and a desire to look "normal."

System Thinking

Basic system concepts are emphasized by identifying and analyzing home components and their interconnections. Figure 5 is a photo of one of the team's initial house systems map. Note that they make connections to cold and hot water supply, electricity, and sewage. They also learn how nearly every appliance gives off heat which affects the operation and energy use of the heating and cooling systems. By introducing the concept of energy efficiency, they learn that this heat, though helping to heat the house in the heating season, is produced much less efficiently than heat produced by modern heat pumps. Plus the electricity used by appliances contributes directly to energy use and the size and cost of the renewable energy systems. A specially developed spreadsheet tool, the ZEH Calculator, accounts for these interactions and allows the student designers to see how design choices affect the overall energy use.

ZEH Calculator

This spreadsheet tool, was developed by Prof. Lau in support of the middle school curriculum project. A copy of the input and output screen is shown in Figure 6. This tool is derived from over thirty years of experience in solar energy analysis and building energy use modeling. It accounts for the passive solar heating benefits of the windows, the heating effects of appliances, the local climate, the thermal integrity of the building envelope, and the performance of solar water heating and solar electricity systems. Currently it includes only Pennsylvania locations, but could readily be modified for other places. There are three outputs, first a pie chart showing the heat loss breakdown and second, a table and chart showing the annual electricity use with solar contributions. As students change parameters, the effect is instantly displayed in the output. This tool is available for use by others by contacting Prof. Lau.

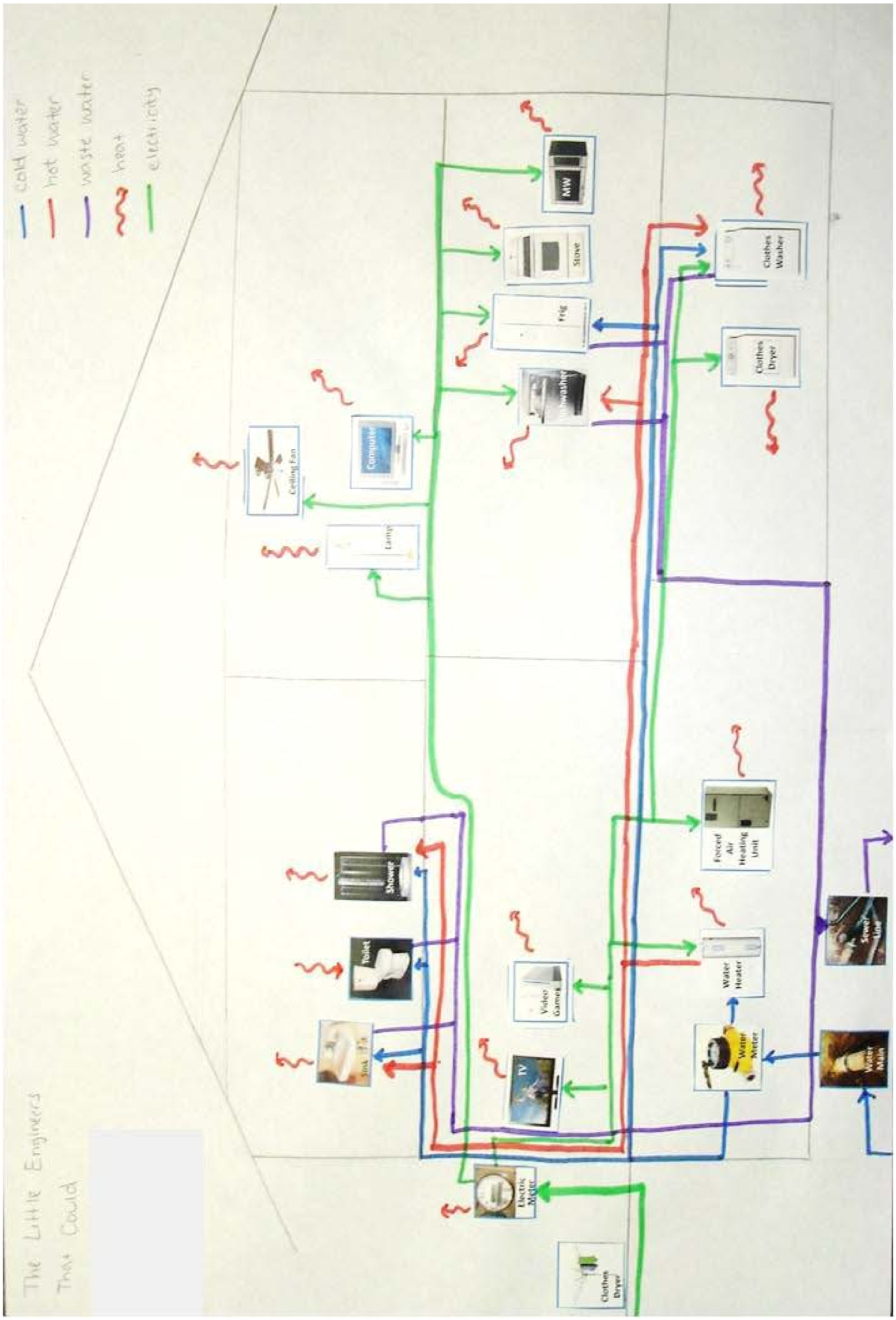

Figure 5 House systems map showing interconnections and interactions

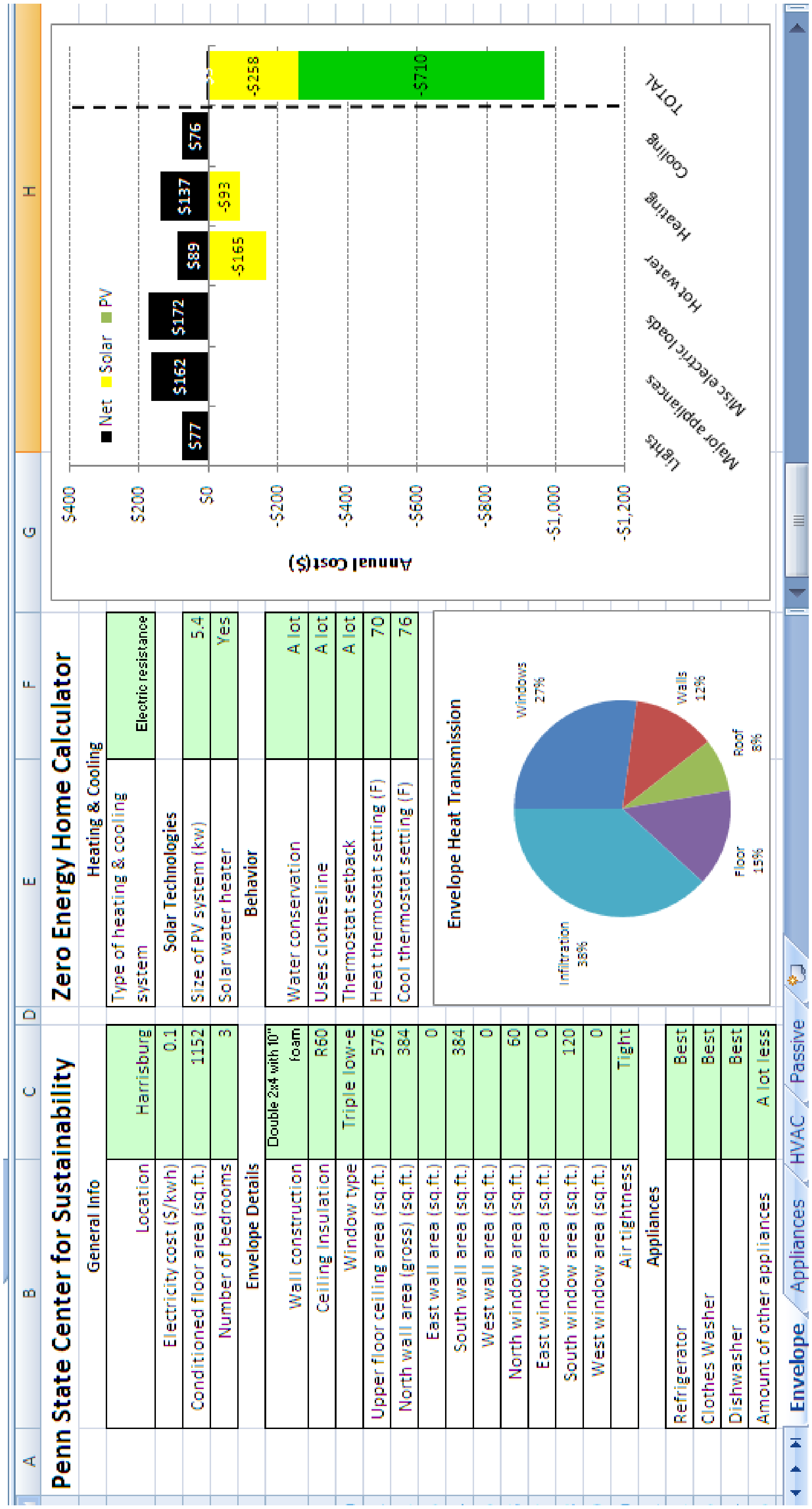

Figure 6 Sample input and output for the ZEH Calculator

In addition to instantly providing feedback on the impact of design choices on energy use, the calculator is used near the end of the design process to size the photovoltaic array in order to zero out the energy use. By inputting a system array size in kilowatts, a trial-and-success process is used to find the array size that results in a zero net annual energy cost. For the house described in Figure 6, an array size of 5.4 kw is the needed size as indicated by the rightmost bar having no black portion. This house being analyzed is an actual ZEH that Prof. Lau helped design in Harrisburg, Pennsylvania. Notice too that the bars are colored to show the cost contribution of solar water heating and passive solar (both yellow), along with the solar electric contribution (green).

Economics

One important element missing from the ZEH Calculator that students pick up on right away is that there is no information on the cost of the various building elements. Having initial cost built into the calculator would indeed be a good addition and be more representative of a real project. Because most students have little understanding of engineering economics, they do an activity involving choosing the most economical clothes washer. Teams start by making a system sketch of the clothes washer and its related components; see Figure 7. This leads to accounting of the various costs of operation: electricity for water heating, running the washing machine, and running the dryer; water; and sewage.

Next the federal energy standards for clothes washers and the EnergyGuide label are analyzed. This allows for an accounting of all of the costs which are not fully accounted for otherwise: dryer energy cost, water cost and sewage cost. Using representative electricity and water and sewage costs for the area, a typical breakdown is shown in the pie chart in Figure 8. Total annual operating cost for this washer is $97 a year. The EnergyGuide label for this washer says it costs $12 a year. The label does not account at all for the cost of water and sewer, which are about half the total annual operating costs. Nor does it account for the dryer energy which is the largest single contributor to operating cost at 39%.

After these in-class exercises, students are assigned homework to gather data online for four different washers (one for each team member), including purchase price. In the following class, they are introduced to the concepts of initial cost, operating cost, and simple payback. Generally, more efficient washers cost more to purchase, but one thing this exercise highlights is that a highly efficient model costs the buyer less over the life of the appliance.

This cash flow analysis is emphasized again with an activity on the costs and savings associated with a photovoltaic electric system. This is facilitated with another spreadsheet that they only need to enter initial costs and financing options. It compares paying cash, a short-term loan (10 years), and a mortgage loan (30 years). It also accounts for tax deductions for mortgage interest, Renewable Energy Credits, and rebates.

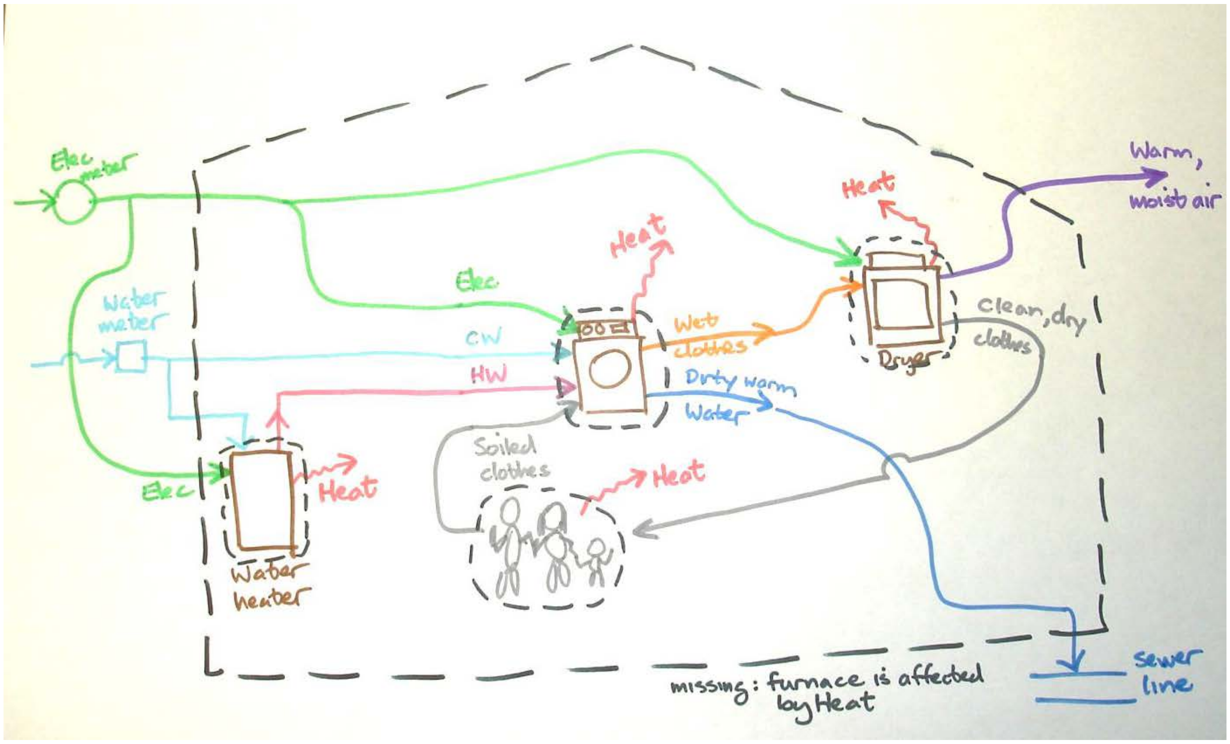

Figure 7 System schematic of a clothes washing system

Sustainability

Students are introduced to sustainability through calculating their ecological footprints and determining lifestyle changes they can make to reduce them.

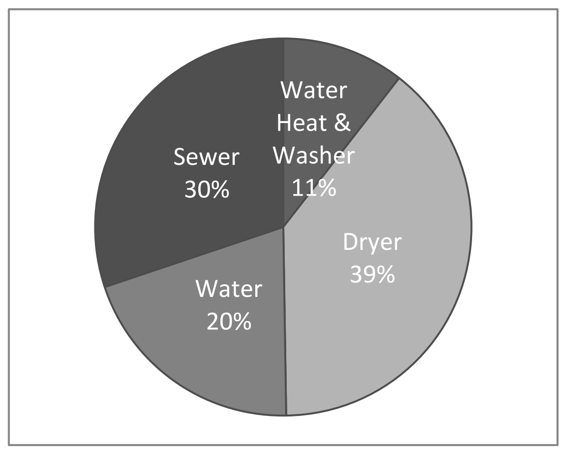

Figure 8 Clothes washer system operating cost breakdown

The important messages for students are:

1) We are currently exceeding the Earth's ecological carrying capacity by 50%;
2) By 2050, current trends are for negative environmental impact to be 4-7 times worse than now; and
3) Achieving environmental sustainability is a combination of better technologies and better behavior.

To engage the students in a gross level understanding of environmental impact, the IPAT concept is used[2] :

I = P A T
Environmental Impact = Population x Affluence x Technology

This formula is used to gauge the overall effect of people on the environment for comparison with the Earth's carrying capacity. This formula can also help to consider options to reduce our impact. Let's look at each of the three terms on the right hand side of the equation.

Current world population was 7.0 billion at the end of 2011. The United Nations projections for world population predict 9.3 billion by 2050.[3] Relative to today, that is an increase of 1.3 by 2050. This year is used because current students will be about 58 years old then and near the end of their professional careers.

The second component of impact is affluence, i.e., how much stuff a person has. Worldwide, affluence is estimated to increase by a factor of 3 to 5 by 2050.[4] While this seems like a large increase in only 40 years, consider that in the last 40 years, world GDP per capita, one way to describe affluence, went from $781 in 1970 to $9,216 in 2010, an increase by a factor of 12![5] It may well be that the estimate of 3 to 5 is low based on recent history. While engineers do not directly affect the desire for stuff, this factor has the most effect on our future impact and the chances for a sustainable world.

The third aspect, impact, however, is very much the realm of engineers – technology. With regard to impact, technology refers to the level of resource use and waste generation associated with a certain level of technological development. In other words, technology attempts to account for the environmental impact of making our stuff (affluence).

Consider that by 2050, P will increase by about 1.3, and A by a factor of 3 to 5. Therefore, to maintain the same overall impact will require decreasing T by a factor of 3.9 to 6.5. Combining this with the ecological footprint estimate that we now exceed the Earth's carrying capacity by 1.5 [6] means that by 2050, T must decrease by a factor of 5.9 to 9.8 to live within Earth's means. To make it easier to remember, we use a factor of 10 as our target. This is a daunting goal to be achieved in a span of about 40 years. Remember too that A increasing by 3 to 5 by 2050 may be an underestimate. If instead A increases by a factor of 12, like it did in the previous 40 years, then T would have to decrease by a factor of 23.

These exercises are intended to motivate students and show them that there are significant opportunities for impact throughout their careers to bring our activities in balance with the Earth's capacity. The ZEH project is just one example of how we as engineers can contribute.

Student Feedback

At the conclusion of the first offering of the project in spring semester 2010, students were asked to reflect on their experience and were prompted by these questions:

1. What can you do now that you couldn't do before?

2. How might understanding house systems apply more generally to engineering?
3. What did you learn about solar energy?
4. What did you learn about ZEH's?
5. Were there any experiences working as a team that can help future teamwork?
6. How can you improve your team's performance on the next project?
7. What do you remember most about using SketchUp?
8. Any other feelings or thoughts about what you learned by doing this project?

Overall, the students' responses were positive and demonstrated that the project was a good learning experience. Here are a few selected responses regarding systems (question 2) and ZEH's (question 4):

<u>How might understanding house systems apply more generally to engineering?</u>

- This project applies to engineering overall because it truly demonstrates how interconnected different systems are.
- By grasping the concept of how housing systems work and the way energy moves through a system, I will be able to better understand other types of systems.
- Engineers need to be mindful of how pieces of a system affect each other in order to create efficient and cost-effective designs.
- I can look at system as a whole now and have a better idea of the energy it needs and how it affects its surroundings.
- Engineering is all about bettering the community around us.
- By grasping the concept of how house systems work and the way energy moves throughout a system, I will be able to better understand other types of systems.
- Planning by working on one element at a time does not always result in the best, most functional solution if everything does not work together.

<u>What did you learn about ZEH's?</u>

- Wasteful consumption is unnecessary at all times, but when you are attempting to achieve a ZEH, you also need to implement a ZEL (Zero Energy Lifestyle).
- The main reason why I liked this project was because it made me realize how we can make changes in way we live our lives to be more efficient.
- Overall, the project taught me that ZEH's are not only doable, but they are practical especially in our economy where everyone is trying to stay on their feet financially.
- I also discovered that a ZEH can be aesthetically pleasing and not look like something from outer space.
- Some features may be costly initially, however, after several years of living in the house, it'll eventually pay itself off.
- I learned that placement of windows can be crucial for a house to receive maximum sunlight throughout the day.

- I also learned that the size of the house is the biggest determinant of how much energy the house will use.

The sole frustration expressed by students was working with SketchUp. Because they used a lot of building elements from the SketchUp on-line library, and most added furnishings to the interior of their houses, the file size was large and bogged down our lab computers. The second time the project was offered, students were warned about this and advised to only work on the house exterior. This reduced the problems but the program still ran slow when the drawing was nearly finished. The authors feel that, despite this limitation, SketchUp is the most appropriate software for this type of project.

In Spring and Fall 2011, students were asked more generally to reflect on what they learned from the ZEH project. Here are some selected responses.

- Why aren't all new homes being built to this standard? Zero Energy Homes are a great example of environmentally responsible building and lifestyle.
- Even though the down payment for an energy efficient house is high, the payback is large.
- In a house there are systems within systems. In order to create a zero-energy house one most look through the systems and subsystems.
- Understanding house systems might lead to more efficient engineering on future projects.
- We are now more aware of design decisions that must be made when building a home, and the various technologies available to conserve energy.
- The various systems of a Zero Energy Home can represent how other engineering systems can complement each other within a larger system, as well as being efficient, and environmentally less bad.
- Solar energy is a vast and powerful resource that can be harnessed in many ways, the mode of production is completely clean (the Sun!). Although the production of photovoltaic cells is not.
- Zero Energy Homes, although costly to build, have numerous payback incentives and leave much less impact on the environment.
- In SketchUp, simplicity rules.
- Payback from efficient appliances
- Learned that almost all dream house features could be incorporated into a ZEH
- Hitting all of the engineering fields
- Gaining knowledge of problems occurring today
- Solar energy is a very powerful resource that when used effectively and can provide large amounts of energy.
- Understanding house systems helps us to understand how other machines and vehicles use energy in all other aspects of our world.

Samples of Student Work

The final report of the project team with the highest grade in Fall 2011 was reviewed to illustrate what students are capable of in this project. First here are some images from their SketchUp model showing their house concept from various directions.

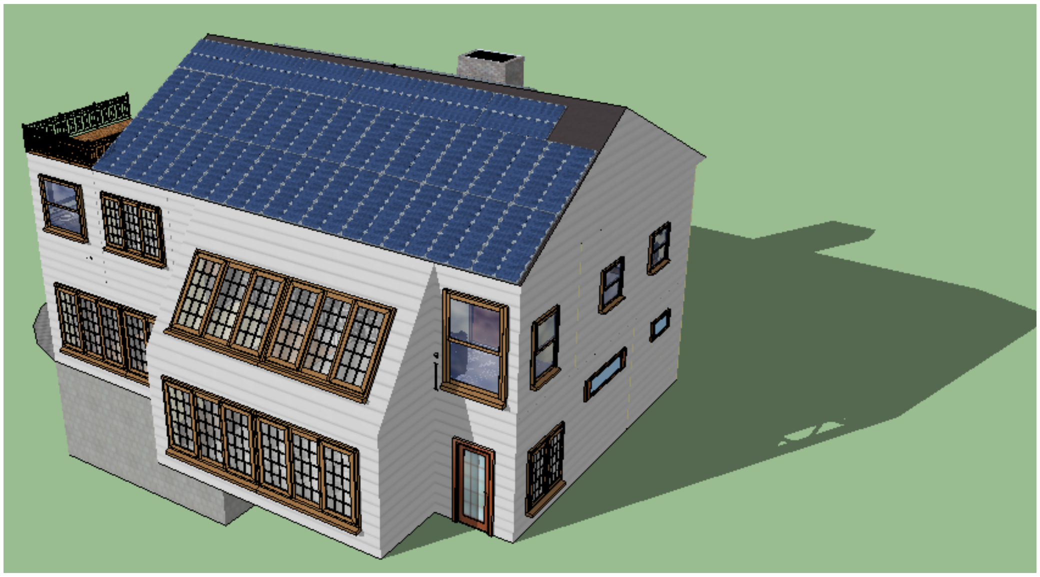

Figure 9 Student concept viewed from southeast.

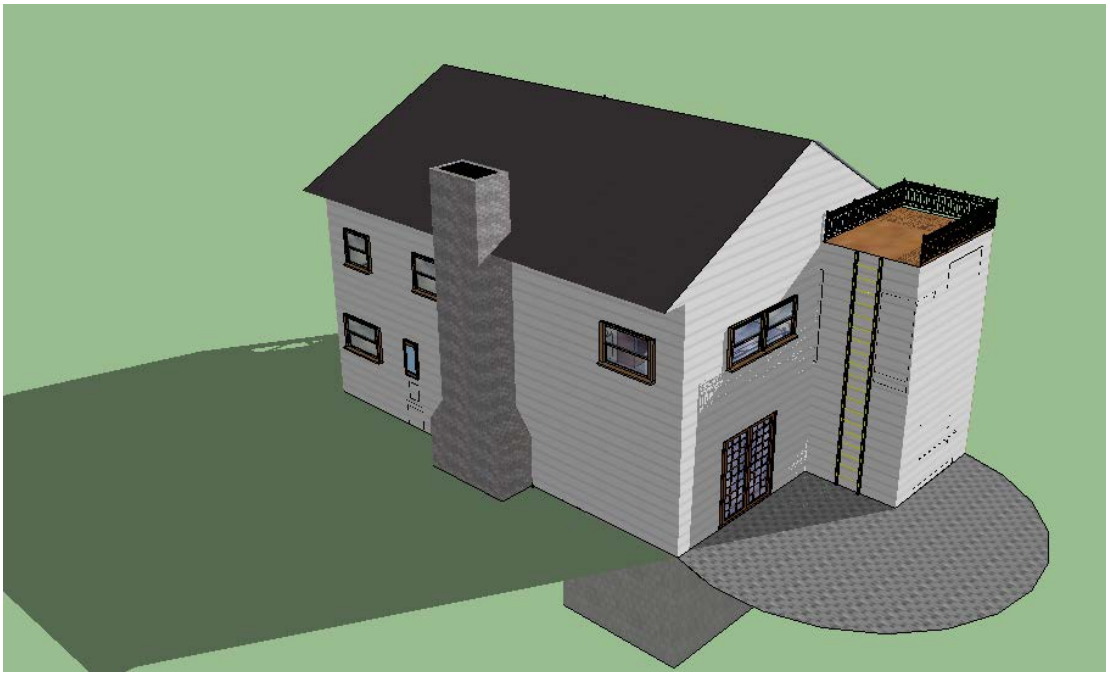

Figure 10 Student concept house viewed from northwest.

In their own words, the students related their form study to the form they chose for their house:

“From class, we knew that to take advantage of passive solar heating, we would want a high south wall surface area. We also knew that the lower the total the surface area of the house, the better it would retain heat, which would result in a lower energy usage. From the isometric study, we concluded that it would be important to have a high length divided by width ratio because it would result in a large amount of south wall. Also, a house with more floors allowed for more south wall area, though it increased the total surface area.”

This design demonstrates the integration of passive solar through the use of a lot of south windows, a large sunspace, open floor plan, and a slab-on-grade floor for most of the ground floor. Rules-of-thumb appropriate for Pennsylvania were used for sizing the south windows and mass floors.

This team also used the insight into simple payback from the class exercise on clothes washers, and applied it to their choice of the main heating and cooling system. They were given cost estimates of four electric heating options. Then on their own initiative they used the ZEH spreadsheet to estimate the annual operating costs of the four options and then to estimate the simple payback times. Though baseboard electric heat was the most cost-effective choice, they chose a heat pump so that the home could have air conditioning. They found that a more efficient air-source heat pump, or a ground-source heat pump, had very long payback times (over 68 years) and were not wise investments. This is not unusual for ZEH’s because they are so well-insulated and efficient that the annual heating and cooling costs are quite low. The basic heat pump they chose, for example, cost $235 a year for heating and cooling.

This paragraph from their conclusion section provides some insight into their big picture learning:

“We gained valuable knowledge from this project. On a large scale, we learned the importance of moving our society toward sustainability. By finding out our ecological footprints, we saw how much it will take to accomplish sustainability in our society. We began to understand the role that each person plays in sustainability. We started to realize that, as engineers, we will have the opportunity to help move our society toward a better place. By creating sustainable designs, we could start to make sustainability a reality in our society.”

Conclusions

The ZEH project provides a timely, relevant and engaging way to introduce first-year engineering students to engineering design. Over the course of its half-semester duration, it touches on every one of the nine course goals for students. One of its strengths is introducing systems thinking, in application to both house systems and their connection to other systems such as energy production, water supply, and sewage treatment. Hopefully, it also motivates students to work toward a sustainable future given the seriousness of the situation.

One of the challenges in EDSGN 100 is making it relevant to all of the engineering majors that are required to take it. Nearly all of the design texts for first-year engineering are about product design. Most of our previous and current first projects are product-based as well. As one of the student teams noted in their reflection, this ZEH project has the advantage of "hitting all of the engineering fields."

All of the resources for this project are available to engineering colleagues by contacting Andy Lau. They have been packaged and outlined in a way that makes the project readily adaptable to other courses.

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