

NET ZERO RESIDENTIAL DESIGN FOR SOLAR CAL POLY
2015 SOLAR DECATHLON HOUSE

A Thesis
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the Faculty of California Polytechnic State University,
San Luis Obispo

In Partial Fulfillment
of the Requirements for the Degree
Master of Science in Mechanical Engineering

by
Bryce Reiko Willis
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COMMITTEE MEMBERSHIP

TITLE: Net Zero Residential Design for Solar Cal Poly
2015 Solar Decathlon House

AUTHOR: Bryce Reiko Willis

DATE SUBMITTED: March 2015

COMMITTEE CHAIR: Kim Shollenberger, Ph.D.
Professor of Mechanical Engineering

COMMITTEE MEMBER: Jesse Maddren, Ph.D.
Professor of Mechanical Engineering

COMMITTEE MEMBER: Steffen Peuker, Ph.D.
Professor of Mechanical Engineering

ABSTRACT

Net Zero Residential Design for Solar Cal Poly

2015 Solar Decathlon House

Bryce Reiko Willis

The Department of Energy (DOE) confirmed Team Solar Cal Poly from California Polytechnic State University, San Luis Obispo, as a competitor in the 2015 Solar Decathlon in February 2014. The Solar Decathlon is a biennial collegiate competition to construct a net-zero home and operate it for a week of “normal use”. Solar Cal Poly needed assistance with passive and active HVAC systems for the design, and thermal load models. The competition will take place in Irvine, CA [33.67⁰, 117.82⁰ W] from September 27 – October 3, 2015. After the completion, a potential final location for the house will be Santa Ynez, CA [34.61⁰ N, 120.09⁰ W]. Ms. Willis assisted with a climate study for both locations and research passive and active HVAC systems and design elements for Team Solar Cal Poly. She modeled the final summer design in DesignBuilder to calculate the heating and cooling loads. The heating load was calculated to be 26.7 kBTU/h. The cooling load was calculated to be 2-tons. A mini-split HVAC system was selected for the final summer design based off the calculated heating and cooling loads. For this design, the Fujitsu Hybrid Halcyon Flex met the minimum requirements, and was a multi-zone system that could condition all three major spaces of the design. This report provides a summary of information and the basic design process for future Solar Decathlon designs considerations.

Keywords: Solar Cal Poly, Solar Decathlon, Net-zero, HVAC

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Table of Contents

	Page
LIST OF TABLES	viii
LIST OF FIGURES	ix
NOMENCLATURE	xii
I. INTRODUCTION.....	1
Statement of Problem.....	1
II. BACKGROUND	3
III. CLIMATE STUDY	11
Average Weather Data	11
Solar Position.....	13
Solar Irradiation	15
Wind Speed and Direction.....	17
IV. LITERATURE REVIEW	19
Previous Solar Decathlon Design Elements	19
Hydronic Heating	19
Split Systems	22
Structurally Insulated Panels (SIPs).....	23
Solar Assisted Heat Pump	24
Passive Building Design Elements	26
Shade Elements and Window Placement	26
Phase Change Materials	27
Thermal Mass	28
Trombe Wall.....	28
Solar Chimney	29
Thermal Roof Pond	31
Insulation	32
Green Roof/Wall	34
Cool Roof Material	35
V. SOLAR CAL POLY PLAN DESIGN PROCESS.....	37
Spring Design Studio	37
Summer Design Studio.....	38
Fall Design Studio.....	41
VI. ENERGY LOAD MODELING	43
CBECC RES.....	44
EnergyPro.....	45

DesignBuilder	46
Surface Heat Balance Manager	49
Climate Calculations	49
Sky Module	50
Sky Radiance Model	50
Shading Module	51
Solar Position	52
Surface Geometry	52
Solar Gains	53
Daylighting Module	53
Window Glass Module	54
Conduction Transfer Function Calculation Module	55
Conduction Finite Difference Solution Algorithm	56
Outside Surface Heat Balance	57
Inside Heat Balance	58
Air Heat Balance Manager	60
AirFlow Network Module	60
Building System Simulation Manager	60
Air Loop Module	61
Zone Equipment Module	61
Economics Calculations	62
VII. Design Builder Energy Model Results	63
VIII. HVAC SYSTEM DESIGN	70
IX. CONCLUSION	78
WORKS CITED	80

LIST OF TABLES

Table		Page
3-1.	A summary of average insolation by month for Irvine, CA and Santa Ynez, CA from PVWatts® solar calculator. (PVWatts Calculator, 2014)	..... 16
6-1.	A summary of the heating and cooling model results comparing the more conventional house design with a house with a full wrap around the exterior for the 2015 competition week in 2015.	..... 65

LIST OF FIGURES

Figure		Page
2-1.	The average global ocean surface temperature since 1880. The grey shaded region shows the range of uncertainty in the collected data. (Climate Change Indicators in the United States, 2014)	..... 4
2-2.	The figure summarizes the U.S. Energy Information Administration (EIA) 2014 reports regarding the delivered energy broken down by sector. Residential and Commercial buildings make up approximately 27% of the delivered energy consumption. (Early Consumption, n.d.)	..... 5
2-3.	The Summary graph of the 2007 IEPR from the CEC. This graphs shows that although the United States' energy consumption has been steadily increasing in kWh/person. California has mostly flattened since the CEC energy efficiency building codes went into effect in the 1970's. (Executive Summary , 2007)	..... 7
2-4.	The summary of residential energy usage broken down by type from the EIA Residential Energy Consumption Survey (RECS). The chart shows that the percentage of energy usage attributed to space condition is no longer the largest energy consumption in US households. (Residential Consumption, 2009)	..... 8
2-5.	This chart shows the efficacy of various lighting technologies. The shaded region shows the approximately efficacy for an entire lighting fixture including losses due to drivers, thermal differences, and optical systems. The black box is the range of efficacies for a range of bare lamps due to construction, materials, wattage, and other factors. (LED Energy Efficiency, 2013)	..... 10
3-1.	The average high and low temperatures for a standard mean year in Santa Ynez (right) and Irvine (left).	..... 12
3-2.	The above solar path charts show the angle of the sun at various times through out the year at the competition site, Irvine (above), and the potential final site, Santa Ynez (below). The chart was generated with the University of Oregon SRML program. (Sun Path Chart Program, 2008)	..... 14
3-3.	The wind roses show the average wind intensity and direction of the competition site, Irvine(left), and final	..... 17

site, Santa Ynez (right). The wind roses were generated with Iowa Environmental Mesonet (IEM). (IEM Site Information, 2014)

4-1.	An example of the layout for a hydronic heating system. Concrete would be poured over the pipes. (Russel, 2012)	.....	20
4-2.	The layers of a SIP come preassembled allowing for faster construction and more even insulation.	.....	23
4-3.	The schematic drawing of Team Ontario’s Solar Assisted Heat Pump system used in conjunction with an Energy Recovery Ventilator and air handler to condition the space. (Ontario, 2012)	.....	25
4-4.	Simple diagram of a Trombe wall with vents in operation.	.....	29
4-5.	A modified Trombe wall design to make a solar chimney.	.....	30
4-6.	The basic design of a solar chimney found in many ancient Middle Eastern buildings. (It's Been Hot, 2008)	.....	31
4-7.	A basic example of heating-season operating procedure for a thermal roof pond.	.....	32
4-8.	A green roof in Portland, Oregon. (Green Roofs, 2013)	.....	35
5-1.	The final floor plan for the Solar Cal Poly entry from the summer design studio. (Poly, 2014)	.....	39
5-2.	A rendering of the Final Summer design showing the slatted shade elements. (Poly, 2014)	.....	40
5-3.	A section view of the slatted wrap element in the final summer design from the 9 October 2014 DOE design submittal. (Poly, 2014)	.....	40
5-4.	The Fall Studio Design rolled out this floor plan after the October 9 th DOE submittal. (Poly, 2014)	.....	42
6-1.	A diagram of the calculation methodology used by EneeryPlus and DesignBuilder.	.....	47
7-1.	The three-dimensional model of final summer floor plan created in DesignBuilder.	.....	63

7-2.	Chart of DesignBuilder calculated loads on condition space for a hypothetical October 1 st for a house design with a 4-inch air gap.	.....	67
7-3.	Chart of DesignBuilder modeled indoor air temperature and relative humidity with respect to outdoor dry-bulb temperature the entire competition week for the 2015 Solar Decathlon.	.....	68
7-4.	Chart of DesignBuilder calculated cooling load on condition space for a hypothetical October 1 st for a house design with conventional materials.	.....	69
8-1.	The 3-ton condensing unit for the Fujitsu Hybrid Halcyon Flex. (Halcyon Hybrid Flex Inverter, 2013)	.....	73
8-2.	The layout of the cassette positioning in the final summer design 2014 floor plan. The coolant lines will run back to the mechanical room, and then outside to the condenser once the building is assembled on site. (Poly, 2014)	.....	75
8-3.	A view of the HVAC and plumbing system for the summer 2014 floor plan as it was submitted on October 2010. (Poly, 2014)	.....	76
8-4.	The Revit model of just the HVAC equipment submitted to the DOE for the 9 October 2014 design documentation. (Poly, 2014)	.....	77

NOMENCLATURE

Ft³ – cubic feet, an imperial unit of volume

BTU – British Thermal Units, an imperial unit of energy

HRV – Heat Recovery Ventilation, a ventilation system with a built in heat exchanger to minimize heat losses and gains from bringing in 100% outdoor air into conditioned space.

HVAC – Heating, Ventilation, and Air Conditioning

Imperial – a system of units still used by the United States based on an older British system of units

SI – Le Système International d’Unités, the international system of units used by the majority of the world

Solar PV – Solar Photovoltaics – a device for generating electricity from direct solar radiation

W – Watts – a SI unit of power.

I. INTRODUCTION

Statement of Problem

Starting in 2002, the United States Department of Energy (DOE) began sponsoring a competition called the Solar Decathlon every two years. California Polytechnic State University, San Luis Obispo, has a team, Solar Cal Poly that is participating in the upcoming 2015 competition. Therefore, Solar Cal Poly's architecture and engineering team must design a net zero home that meets both the competition and a potential customer's requirements. An accurate building thermal load and energy model will ensure that the final design meets the criteria for a net zero home.

Ms. Willis will research passive and active thermal control systems for possible use in the Solar Decathlon design. By definition, passive systems use the principles of heat transfer to keep interior spaces comfortable without electricity. Many passive systems rely on the properties of thermal mass, for example Trombe walls and solar chimneys. The design of systems like these will hopefully be used to offset some of the heating and cooling loads of the competition house.

Once the passive design elements have been incorporated into the house design, and the house has been modeled. The heating and cooling loads will be used to size active HVAC equipment to make sure the house meets the Solar Decathlon competition requirements for temperature, humidity, and ventilation. There are many existing computer models that can calculate accurate thermal loads based on an architectural design. One such modeling software is DesignBuillder.

This project hopes to fulfill three objectives. First this project wants to assist with the design of Solar Cal Poly's entry to ensure the final house design emphasizes passive design elements to reduce heating and cooling loads. Second, this project looks at the heating and cooling loads of Solar Cal Poly's Decathlon final house design and provides a preliminary design of the HVAC system. Finally, this project hopes to layout the basic information and methodology necessary to assist Solar Cal Poly with finishing the 2015 Solar Decathlon completion entry and future Cal Poly Solar Decathlon contest entries.

II. BACKGROUND

The availability of cheap fuel and electricity created the large scale manufacturing, economic growth, and improvement in quality of life indicative of the 20th century. Energy usage in the United States has increased steadily since the turn of the century. According to the U.S. Energy Information Administration (EIA), the U.S. consumed an estimated 9.6 quads (quadrillion BTUs or 10^{15} BTU) in 1900. At that time the major energy source was coal. (Total Energy, 2012) By 2010, the U.S. consumed 98.0 quads. Although 2010 had many more energy sources, over 80% of energy consumption in this country still came from fossil fuels. (Monthly Energy Review, 2014)

By definition, fossil fuels are composed of various combinations of carbon and hydrogen atoms. For example, the natural gas used in residential heating and cooking is composed of one carbon atom bonded with four hydrogen atoms, CH_4 . The gasoline used by most cars is eight carbons bonded with fourteen hydrogen atoms, C_8H_{14} . The combustion of fossil fuels breaks the bonds between the hydrogen and carbon atoms which recombine into water vapor and greenhouse gases (GHG), like carbon dioxide (CO_2). In 1961, CO_2 emissions from the United States was 2,834 metric tons of CO_2 equivalent (MtCO_2eq). In 2010, that value had ballooned to 218,382 MtCO_2eq . (Historical GHG Emissions by Gas, n.d.)

Solar radiations, often called short-wave radiation, originates from the sun in the wavelength range of 0.3 – 3 micrometers (μm). The heat from the solar radiation is absorbed by the earth, and then re-emitted as long-wave radiation. (Beckman, Solar Engineering of Thermal Process, 2006) Much of this long-wave radiation escapes the

atmosphere. The rest is reflected back to earth and trapped by GHGs. This reflection of the long-wave radiation is called the greenhouse effect. Just like in a garden greenhouse, the trapped heat keeps the earth warm. But with the significant increased GHG emission in just the last hundred years means that more long-wave radiation is being trapped in the atmosphere. The increase in trapped long-wave radiation has cause a measurable rise in global ocean temperature. According to the National Oceanic and Atmospheric Association (NOAA), the ocean surface temperature rose an average of 0.13⁰F per decade since the 1970's. Figure II-1 shows this trend. (Climate Change Indicators in the United States, 2014)

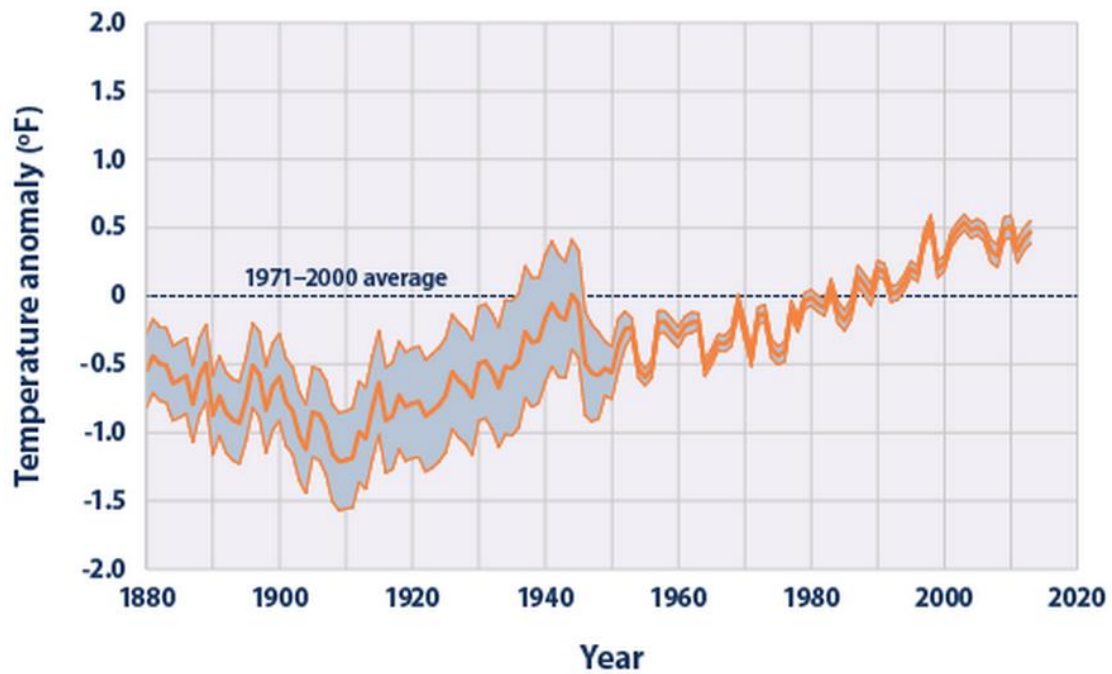


Figure 2-1. The average global ocean surface temperature since 1880. The grey shaded region shows the range of uncertainty in the collected data. (Climate Change Indicators in the United States, 2014)

Recently, it has become clear that this steady rise in energy usage is unsustainable. As the evidence of global warming mounts, efforts need to be undertaken to slow and reduce the country’s GHG emissions. As can be seen in Figure 2-2, industrial and transportation use the most delivered energy, with residential and commercial building making up approximately 30% of the United States’ delivered energy consumption.

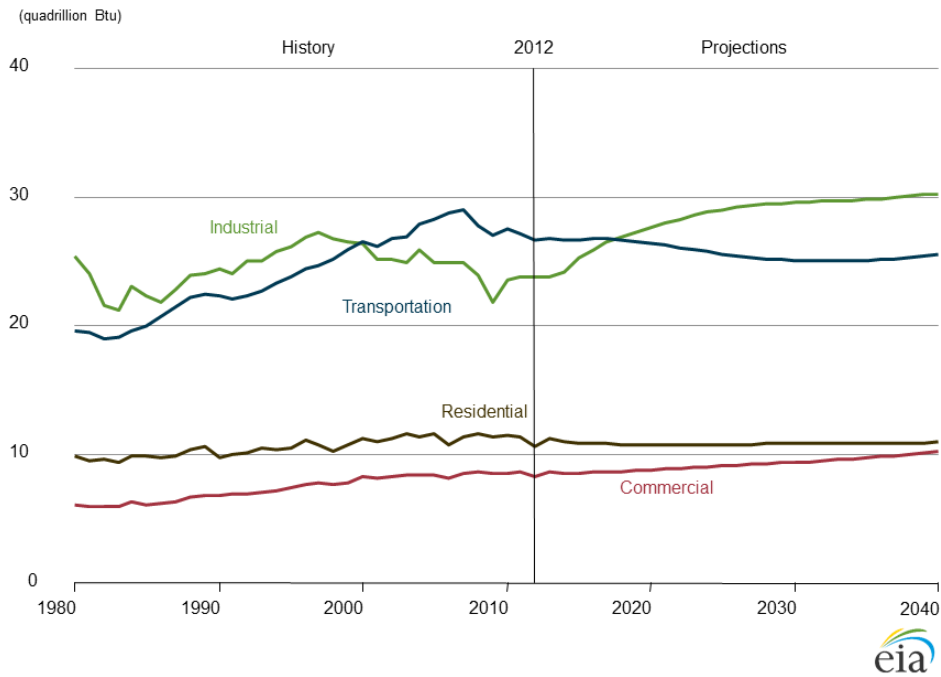


Figure 2-2. The figure summarizes the U.S. Energy Information Administration (EIA) 2014 reports regarding the delivered energy broken down by sector. Residential and Commercial buildings make up approximately 27% of the delivered energy consumption. (Early Consumption, n.d.)

Delivered energy can also be called net energy or site energy, and it is the amount of energy that is used by the building or vehicle. It does not take into account the energy losses associated with power plant generation and transmission to the site. The site usage, generation losses, and transmission losses are combined to make the total energy use, also called source energy. So although site energy is useful for measuring energy efficiency at

a particular site, those numbers alone do not accurately measure the full energy usage and GHG costs.

Any energy generated on-site with generators or solar PV panels is called primary energy. Producing energy on site eliminates transmission losses in the wires. Additionally, primary energy generation reduces the demand load on central plants. Therefore, even if the site has not reduced its site energy consumption, the site has still reduced its source energy consumption, or secondary energy usage. A system of energy generation that reducing the demand for large central power plants by creating more on-site energy generation is called “distributed generation”.

In an attempt to increase the amount of distributed generation, the California Energy Commission (CEC) has instituted a goal to have all new residential construction net zero by 2020, and all new commercial construction net zero by 2030. Net Zero is defined as a building that generates all its energy needs on-site with renewables, and therefore reduces the load on utilities and the production of greenhouse gases. Since the CEC began making energy efficiency part of the building code in California in the 1970’s the energy usage in kWh per person has flattened out while the rest of the United States is showing a steady increase as shown in Figure 2-3.

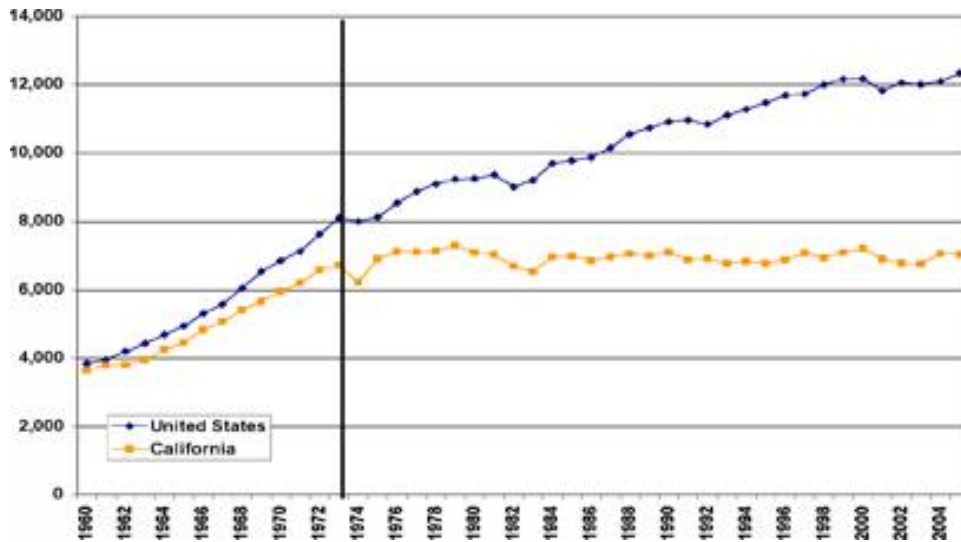


Figure 2-3. The Summary graph of the 2007 IEPR from the CEC. This graphs shows that although the United States' energy consumption has been steadily increasing in kWh/person. California has mostly flattened since the CEC energy efficiency building codes went into effect in the 1970's. (Executive Summary , 2007)

Over the last few years, there has been a significant improvement in residential energy efficiency. As shown in Figure 2.2, the gap between commercial and residential energy consumption has decreased and is projected to continue to decrease. The most obvious cause of this change is shown in Figure 2-4. According to the EIA, in 1993 the majority of energy usage in residential buildings was HVAC. But in the current 2009 report that is no longer the case.

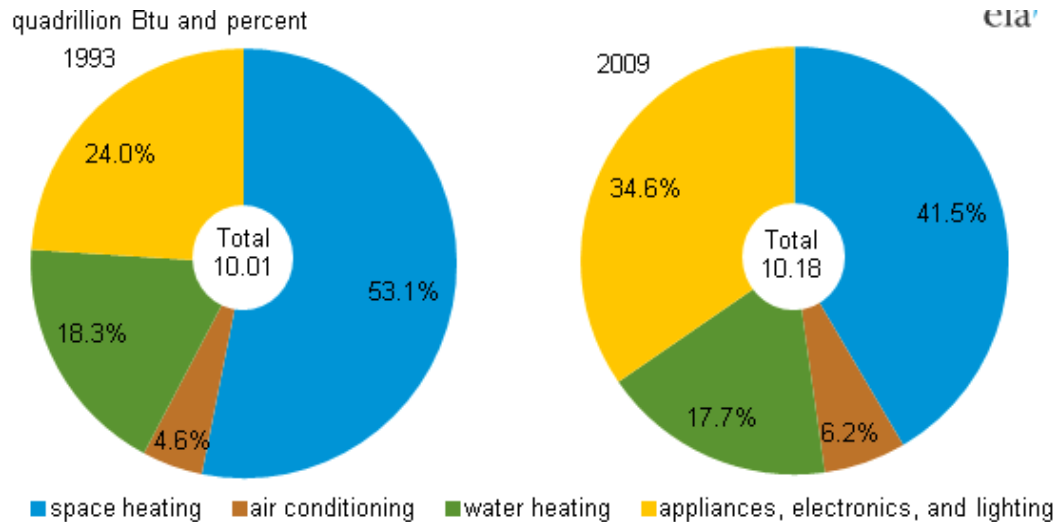


Figure 2-4. The summary of residential energy usage broken down by type from the EIA Residential Energy Consumption Survey (RECS). The chart shows that the percentage of energy usage attributed to space condition is no longer the largest energy consumption in US households. (Residential Consumption, 2009)

Extrapolating from the EIA Residential Energy Consumption Survey (RECS), approximately 2.4 Quads of energy used for appliances, electronics, and lighting, 5.8 Quads was used on space conditioning, and 1.8 Quads was used on water heating in 1993. While in 2009, 3.6 Quads were used on appliances, lighting, and electronics, 4.9 Quads were used for space conditioning, and 1.8 Quads were used for water heating. This data shows that the amount of energy used for space conditioning has decreased from 5.8 Quads in 1993 to 4.9 Quads in 2009, a 15.5% decrease in usage. This decrease shows how the improvements in HVAC system efficiency and operation have made a difference. A more concerning result is that lighting, appliances, and electronics have increased by approximately 50%. This rapid growth is mostly likely due to the dramatic increase in the electronics we have today, such as computers, laptops, and cell phones. The increase in the “plug loads” energy usage has all but erased the reduction in energy usage, which is why the net energy usage by residential buildings still has increased. There was not a

significant change in the water heating energy usage between 1993 and 2009. There have not been many advancements in water heating efficiency, but since water heating makes up so little of the total energy usage, most efficiency efforts are going towards the places that can affect the greatest portion of the pie. One recent advancement in lighting that may not be included in the 2009 data is the emergence of light emitting diode (LED) lighting technology. LEDs only recently became economical to start putting into homes for day-to-day lighting needs, but they use significantly less energy than conventional light bulbs, last nearly twice as long as compact fluorescent lamps (CFLs), and have higher lighting efficacy. Lighting efficacy is a ratio of power input to light output. According to the DOE, the target efficacy of LEDs 200 lumens per watts squared (lm/W^2). The current ranges of lamp and fixture efficacy by luminare type is summarized in Figure 2-5. (LED Energy Efficiency, 2013)

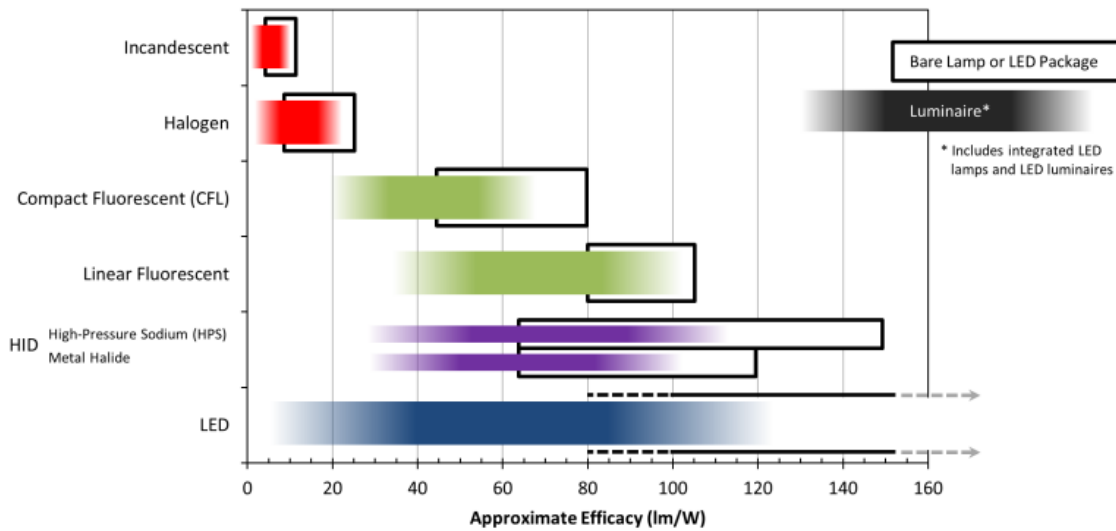


Figure 2-5. This chart shows the efficacy of various lighting technologies. The shaded region shows the approximately efficacy for an entire lighting fixture including losses due to drivers, thermal differences, and optical systems. The black box is the range of efficacies for a range of bare lamps due to construction, materials, wattage, and other factors. (LED Energy Efficiency, 2013)

In an effort to encourage young people to get involved and innovate the future of building technology used to reduce energy usage in buildings, the DOE started a competition that pitted colleges across the world in a race to produce the most livable net zero home, the Solar Decathlon. The homes are installed at the competition site and operated over a week to demonstrate their ability to perform tasks typical for any conventional house. Some tasks include running the shower for thirty minutes while maintaining a temperature of 120⁰F, washing dishes in a dishwasher, and having a group of people over for a movie night. Most importantly for this project, the Solar Decathlon completion requires that the interior of the home stay between 70⁰F and 75⁰F with less than 60% humidity for the entire length of the competition. (Solar Decathlon Rules, 2014)

III. CLIMATE STUDY

The California Polytechnic State University, San Luis Obispo (Cal Poly) was one of 18 teams selected to compete in the 2015 Solar Decathlon competition. A potential customer for the Cal Poly solar house was found to be a tribal leader for the local Chumash Native American Tribe. The competition will be held in Irvine, California and the final potential location of the house may be in Santa Ynez, California. For net-zero building construction, the actual location of the house significantly affects the design and final performance of the house.

The following analysis compares the climate of the competition site in Irvine with the potential final destination of the house in Santa Ynez. Both sites are located in southern California. Irvine is approximately located at 33.7⁰ N, 117.8⁰ W. Like much of southern California, the climate is considered Mediterranean, summers are warm to hot, winters are cool to warm, and the area rarely freezes. Precipitation is rare, but occurs predominately during the winter months. Irvine is in Climate Zone 8 (Joint Appendix JA2 - Reference Weather/Climate Data, 2013). Irvine is about seven miles from the Pacific Ocean (Irvine, California, 2014). Santa Ynez is located at 34.6⁰ N, 120.1⁰ W. Although, Santa Ynez is located in Climate Zone 5, Santa Ynez is also considered to have a Mediterranean climate, with warm (not hot) summers, and nearly all of the precipitation in the winter months (Joint Appendix JA2 - Reference Weather/Climate Data, 2013). Santa Ynez is approximately ten miles from the ocean.

Average Weather Data

Temperature data can be used for thermal modeling and provides a good baseline on the conditions the house will need to handle throughout the year. The average high and low

temperatures for a standard mean year in Santa Ynez and Irvine are shown in Figure 3-1. Average highs and lows give insight into what conditions a specific site will undergo, and will help with early design development.



Figure 3-1. The average high and low temperatures for a standard mean year in Santa Ynez (right) and Irvine (left).

Santa Ynez has a slightly larger temperature differential from high to low than Irvine. Santa Ynez gets about 5⁰F warmer and 10⁰F cooler in the summer than Irvine. During the winter months, Irvine and Santa Ynez temperatures are more similar. The final design should be able to work at both sites.

Because the climate is temperate and stays between a similar temperature range throughout the year, the final design should focus on passive elements that smooth out temperature fluctuations, like thermal mass. Thermal mass will be discussed more in Chapter 4. For

the final design model, DesignBuilder's built-in sub-hourly weather data was used to more accurately model the thermal loads and energy use of the house design.

Solar Position

The position of the sun in the sky is used to find the amount of direct solar gains an exterior surface is exposed to. This direct solar radiation causes a temperature rise within the space.

Solar path charts show the position of the sun throughout the year. The solar path charts for Irvine and Santa Ynez are shown in Figure 3-2. The blue curves are the position of the sun over the course of one day a month from the winter solstice to the summer solstice.

The red lines represent time of day.

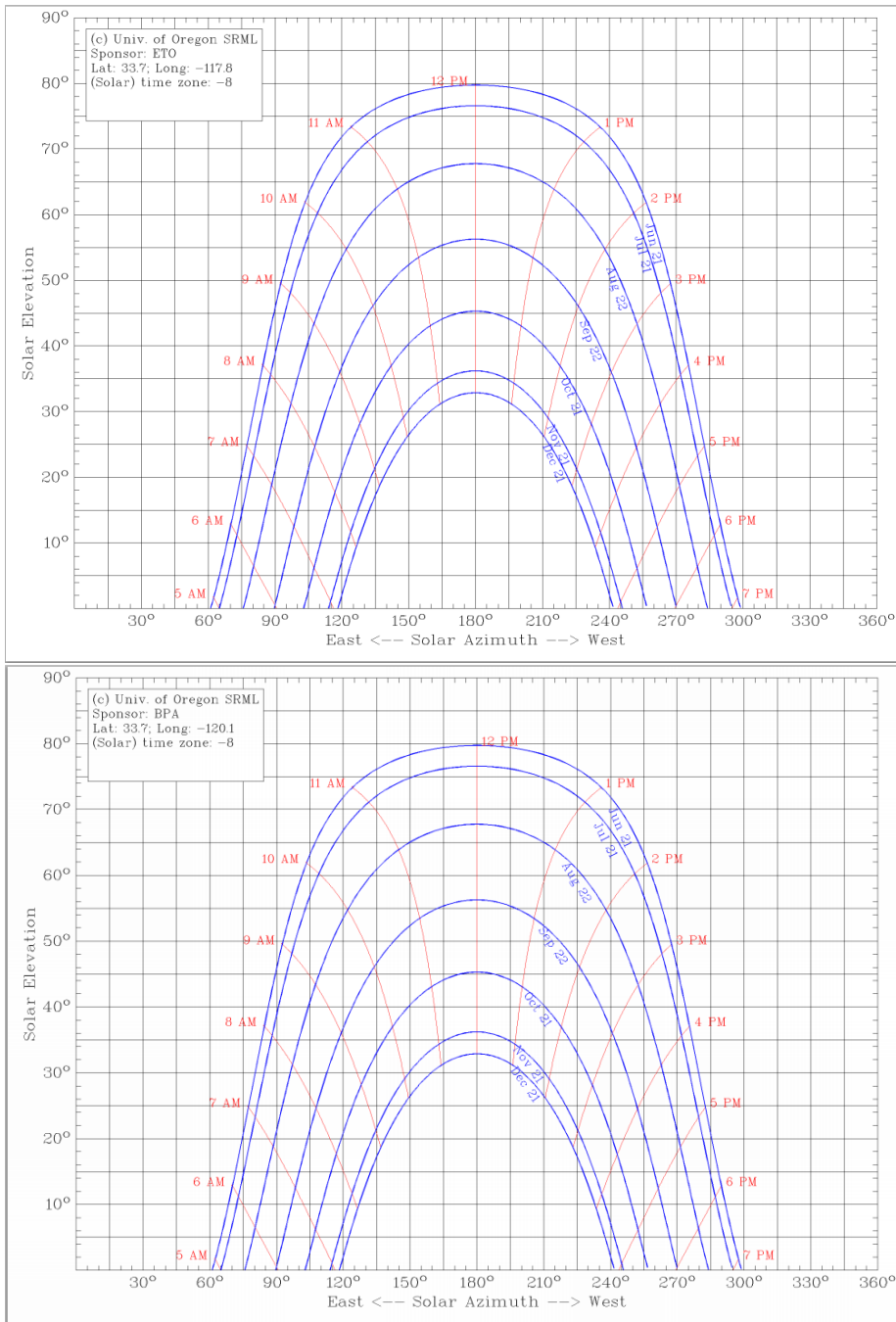


Figure 3-2. The above solar path charts show the angle of the sun at various times through out the year at the competition site, Irvine (above), and the potential final site, Santa Ynez (below). The chart was generated with the University of Oregon SRML program. (Sun Path Chart Program, 2008)

These solar path charts show the position of the sun based on the solar azimuth angle (γ) and the solar elevation angle (α). Solar azimuth is the angular displacement of the sun's

position projected onto the horizontal plane. Normally for a Northern Hemisphere site, the South is 0° , east is negative, and west is positive. (Beckman, 2006) The charts created by the University of Oregon SRML program treats South as 180° with due East being 0° and due West being 360° . The solar elevation angle is the angular displacement of the sun vertically from the horizontal plane, where 0° is the horizontal and 90° is the straight overhead. Solar path charts are commonly used to design shade elements to shade windows in the warmer months, while letting in the solar radiation in the cooler winter months.

The solar path charts are very similar for both sites. Both charts have a highest solar elevation angle of 80° at solar noon (when the sun is at its highest point during the day).during the summer solstice. Both charts have a lowest solar elevation angle of 33° during the winter solstice. The similarities between the two charts mean that the shading elements used at the competition site should work the same when the house is at its final site.

Solar Irradiation

Another piece of the puzzle is the actual amount of solar irradiation, or insolation, on the respective sites. Although the sun may be in the same relative position in the sky, if one site has different levels of cloud cover that will drastically affect the requirements of the house. The average insolation of the competition site and final site is shown in Table 3-1. (PVWatts Calculator, 2014)

Table 3-1. A summary of average insolation by month for Irvine, CA and Santa Ynez, CA from PVWatts® solar calculator. (PVWatts Calculator, 2014)

Average Solar Radiation (kWh/m ² /day)		
Month	Irvine	Santa Ynez
January	3.11	2.92
February	3.35	3.76
March	5.28	4.56
April	6.08	6.51
May	6.00	6.97
June	7.16	5.04
July	7.29	6.54
August	6.54	5.48
September	5.52	5.11
October	3.77	3.89
November	3.47	3.28
December	2.88	2.38
Annual Average	5.04	4.70

There is a limited number of weather stations that PVWatts® pulls data from. The data used for the Irvine site comes from the weather station at the Santa Ana John Wayne Airport, approximately five miles from Irvine city center. Santa Ynez is more remote. The nearest weather station that PVWatts® has access to is located in Lompoc, approximately twenty-two miles away.

The values entered into PVWatts® to solve for the global solar radiation (radiation incident on a horizontal surface). Some months Irvine has a higher average solar radiation than Santa Ynez, and some months Santa Ynez was higher than Irvine. The annual average shows that Irvine has a higher daily solar radiation than Santa Ynez. This means that

modeling the building thermal loads based on the competition site should produce building loads sufficient for both sites.

Wind Speed and Direction

The final piece of weather data needed to begin laying out an energy efficient house is wind direction. Natural wind flow will help demonstrate how operable windows will affect the passive ventilation of the house. The wind roses for Santa Ynez and Irvine are shown in Figure 3-3. (IEM Site Information, 2014) Like PVWatts®, the wind data is limited to available weather stations. Again, the Irvine data comes from the John Wayne Santa Ana Airport located approximately five miles from Irvine. Santa Ynez wind data comes from a weather station located in Santa Ynez, approximately one mile from city center.

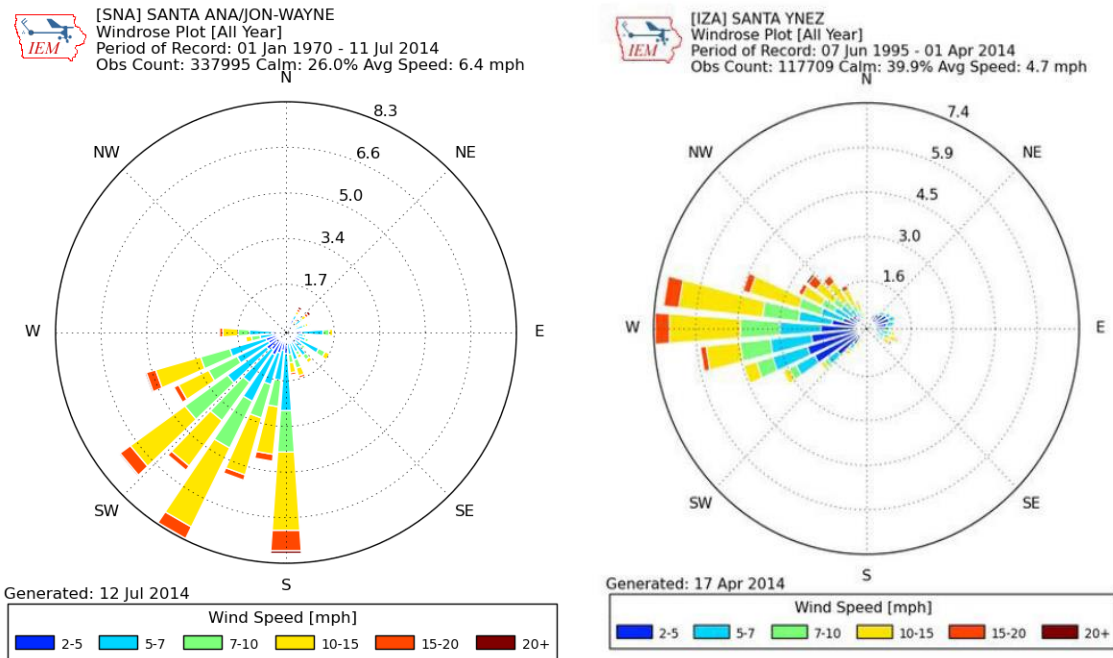


Figure 3-3. The wind roses show the average wind intensity and direction of the competition site, Irvine(left), and final site, Santa Ynez (right). The wind roses were generated with Iowa Environmental Mesonet (IEM). (IEM Site Information, 2014)

Unlike many of the other weather and climate data, Santa Ynez and Irvine have different wind flow direction and speed. Santa Ynez has a fairly narrow band of directions. The majority of the wind is blowing westerly. The wind speed does get over 15 miles per hour (mph), but the average is 4.7 mph. In Irvine, the wind blows in a much more diffuse spread, with a significant amount of wind blowing from due south to south-west. The wind in Irvine averages 6.4 mph with a maximum speed over 20 mph. Extra care should be taken with the natural ventilation models due to the difference between the two sites.

IV. LITERATURE REVIEW

The Solar Cal Poly Decathlon house design needs to contain passive and active building elements to effectively compete in 2015. The following chapter contains a discussion of research into building elements for potential use in Solar Cal Poly's design. The first section summarizes design elements found in previous Solar Decathlon entrees. All the information for this section comes from the 2013 Solar Decathlon Design Documents provided by the Department of Energy. The second section expounds on other state-of-the-art and historic building passive design elements that could also help with the effectiveness of the Solar Cal Poly design. A passive design element is a part of a design that affects the heating and cooling loads of the conditioned spaces without requiring active HVAC equipment that consumes electricity.

Previous Solar Decathlon Design Elements

Previous Solar Decathlon entrees submitted Design Documents to the Department of Energy that summarize the various design elements that each team used to accomplish the Solar Decathlon competition requirements. The 2013 Solar Decathlon Design Documents contain some of the following active and passive design elements that could be incorporated into the Solar Cal Poly 2015 design. This section focuses on the properties, benefits, and complexities of the design element, and does not discuss the specifics of the previous solar decathlon entrée's design.

Hydronic Heating

Team aSUNm and DesertSol, from Arizona State University/University of New Mexico and University of Las Vegas respectively, both use hydronic floor heating systems in their designs. Hydronic heating, in this case, refers to a system with hot water pipes running

through the floors, walls, or ceilings. These hot water pipes heat up the surrounding material, normally cement, and the surrounding material radiates the heat into the space. An example of the hot water piping is shown in Figure 4-1.



Figure 4-1. An example of the layout for a hydronic heating system. Concrete would be poured over the pipes. (Russel, 2012)

Hydronic heating systems actually refers to any system that uses hot water as the heat transfer medium. For example, many old buildings that have wall mounted radiators for heating are also “hydronic heated”. In many of these cases, the hot water travels through a coil in a fan unit and the fan distributes air heated by the water to the respective spaces. In the recent decades, the hydronic heating system describe above has become popular. This system is also referred to as a “radiant floor” system. For the rest of this section, this system will be referred to as a “radiant floor” system to distinguish it from older related systems.

The radiant floor system is more efficient than the older models of hydronic heating because water has a higher specific heat and density than air. Water can transport the heat

energy more efficiently than air. Therefore, more of the heat energy is transmitted to the space. Additionally, most people feel more comfortable in a radiant floor system, because the floor is warm. As the water runs through the floor, the concrete or other floor material warms, and that keeps the entire room feeling warmer. Once the floor is warm, the mass of the floor helps keep the temperature in the space from fluctuating, and therefore the space can maintain the same temperature more easily.

This slow change in the space due to the nature of radiant floors can also be a negative of the radiant floor system. If the floor is cold, it can take a long time for the floor to warm, and the space will not start to feel warm until after the floor heats up. Additional negatives for the radiant floor system are the added expense and complexity of a system. As shown in Figure S1, the pipe layout for the radiant floor system is significantly more complex than a traditional forced air system, and therefore the entire system is more expensive.

The final flaw in a radiant floor system is that they are primarily used for heating. “Radiant cooling” systems have been built, but they have several problems that are not seen in the radiant heating. First, the radiant cooling system must be above the dew point within the house to function properly. This means that the building must be kept dehumidified. According to the U.S. Department of Energy, in humid climates opening a door could be enough to cause condensation. (Radiant Cooling, 2012) Secondly, the optimal cooling system runs through the roof. This means that two separate water systems will need to be installed. Adding expense to the house. Finally, the cooling can make people feel uncomfortable. Normally the water pipes are run through walls or ceilings, and people report the rooms feeling clammy.

Split Systems

Czech Technical Institute (Air House) and Norwich (Delta T90 House) are two 2013 Solar Decathlon teams that used a split system for their major active HVAC equipment. A split system is normally a forced air system, where the heating source and cooling source are located in different locations, such as a furnace in the fan unit and a condensing unit outside, but still typically use the same duct system. The separated (or split) sources alter the temperature of the air with a heating or cooling coil, respectively. The conditioned air is then distributed to the zones by ductwork. The main advantage to this system over the traditional package units is that the various components can be designed to fit the specific needs of a space. For example a house located in the moderate central coast climate may only include the furnace portion for heating in the winter, or only include a smaller outdoor condensing unit for the small amount of cooling load required. Today split systems are very common.

The most recent development in HVAC design is the “mini-split”. Mini-splits rely on an exterior condensing unit that is more compact than most conventional split systems. The outdoor unit of a traditional 2-ton split system is approximately 12.5 ft³ while a 2-ton mini-split is approximately 9 ft³. Additionally, instead of running the refrigerant lines to an internal cooling coil in the fan unit, the coolant lines run to “cassettes” located within the space and a fan in the cassette circulates the air within the space. Another major advantage of the mini-split system is they are more efficient than traditional ducted HVAC systems, because they eliminate the energy losses due to air leaks in the ducts. The DOE estimates that approximately 30% of energy loss in HVAC systems are in the air ducts. (Ductless, Mini-Split Heat Pumps, 2012)

The major disadvantage of mini-splits is that some people consider the cassettes to be intrusive in the décor. The system also does not take in outside air, so a separate method of ventilation will need to be established.

Structurally Insulated Panels (SIPs)

Team Kentuckyana (The Phoenix) and many other 2013 Solar Decathlon entrants used Structurally Insulated Panels (SIPs) in much of their envelope. SIPs are pre-assembled wall units, that fit together easily for tight, quick home construction. A sample layout of a SIP panel is shown in Figure 4-2. A common assembly of SIPs is an oriented strand board (OSB) surrounding a foam core. Common materials for the foam core are extruded polyurethane or expanded polystyrene.

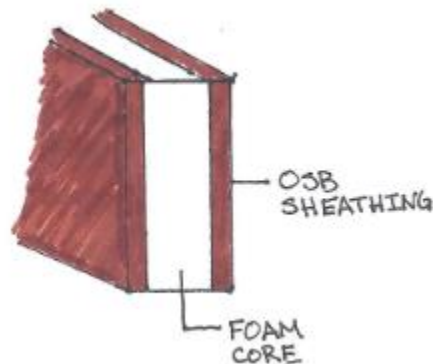


Figure 4-2. The layers of a SIP come preassembled allowing for faster construction and more even insulation.

The main advantage of a SIP building is the wall panels come pre-assembled, so they just need to be put together and finished. This makes construction much faster and easier. Additionally, since the insulation is built into the panel, it reduces the leaking problems

when insulation is not properly installed. Additionally, the insulation R-value can be higher than conventional batt insulation because the foam core has a better resistance to air infiltration and heat transfer.

This tightness of SIP construction is actually one of the major disadvantages as well. The houses require additional ventilation to make sure that fresh air is brought into the interior spaces. Other issues with SIP construction is the added upfront expense.

Solar Assisted Heat Pump

Team Ontario used a solar assisted heat pump (SAHP) in their house design. The basic premise is the solar collector is used to heat a refrigerant, and that heated refrigerant is then used to run a heat pump cycle and to heat a hot water tank. Although, this extra step to just heat water is less efficient than a traditional solar thermal system, used for space conditioning, the SAHP system can reduce the amount of energy required. In general, SAHP efficiency varies from 4 to 9 SEER depending on weather conditions. (Vladimir Solda, 2004) SEER stands for Seasonal Energy Efficiency Ratio. It is a measure of cooling efficiency for air conditioners and heat pumps. It is calculated by cooling output for a typical cooling season divided by the total electric energy input during the same time frame. (SEER, 2014)

The schematic of Team Ontario's SAHP is shown in Figure 4-3.

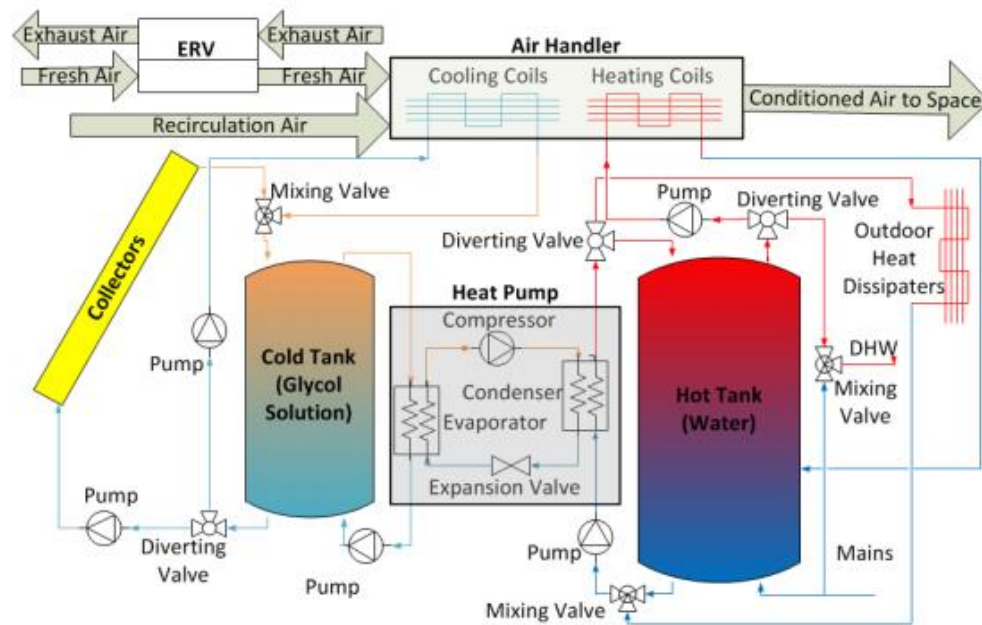


Figure 4-3. The schematic drawing of Team Ontario's Solar Assisted Heat Pump system used in conjunction with an Energy Recovery Ventilator and air handler to condition the space. (Ontario, 2012)

This system is good at providing heating and cooling with minimal energy input. The system relies on a glycol solution in a solar hot water system, to provide a heat pump with a cold reservoir. Because there is fairly little energy input required, the system saves energy even though the system only has a SEER of 4 to 9.

The major downside for this system is that the system must be specially tuned for each environment it enters. The increased system complexity means that the system will be more expensive than some more-conventional HVAC systems, and more difficult to work with as a homeowner.

Passive Building Design Elements

For the majority of human civilization buildings needed to be comfortable without electricity. The methods of keeping buildings comfortable have developed over the centuries, but the passive elements used in early design rely on basic concepts that are still useful in today's powered world. These passive elements rely on solar heat, wind, and the natural properties of some materials to provide heating and cooling control within space. Ideally, the Solar Cal Poly design should incorporate some of the following elements to reduce the heating and cooling loads of the final house design.

Shade Elements and Window Placement

Solar gains are the largest cause of warming in interior spaces. The speed and efficiency of the solar heat transferring into the interior space depends on the thermal properties of the exterior surface and the exterior surface area exposed to the solar radiation. Thermal properties are discussed in later sections. When solar radiation strikes the exterior surface of the building, and warms that surface, that heat is then conducted through the wall to the interior space. When solar radiation passes through exterior glazing, the energy increases the temperature of the interior space. Therefore, limiting the direct solar gains on the walls and glazing of a building can significantly reduce the cooling requirements of the interior spaces. Solar shading relies on the changing azimuth of the sun throughout the year. In the summer, when the sun is higher in the sky and heating is undesirable, the shade is designed to prevent the direct solar gains on the exterior walls. While in the winter, when the sun is lower in the sky and heating is desirable, the solar radiation is able to strike the exterior surface.

The placement of windows and glazing around the building also affects the thermal loads in the spaces. For obvious reasons, in the northern hemisphere, south-facing glass receives more direct solar irradiation throughout the day without shading elements. Eastern and western glazing also produces a significant amount of direct solar irradiation, because the sun is lower in the sky during sunrise and sunset. Shade elements normally do not block the direct solar irradiation into the eastern and western windows during sunrise and sunset, respectively. Therefore, even though they only receive light during part of the day, they can drastically increase the interior cooling loads. This is most dramatic with western windows that begin to raise the interior temperature in the late afternoon when the cooling load is already highest. For these reasons, western and eastern glazing should be minimized if not eliminated, and southern glazing should receive extensive shading in warmer climates, like those in Irvine.

Phase Change Materials

The newest development in thermal mass is phase change material. Phase change materials are specially designed to change state from solid to liquid and back at a certain temperature range. This is useful because as a material undergoes a phase change, it can absorb or release a significant amount of energy without changing temperature. Basically, phase change materials act like a regular thermal mass while taking up less space. Phase change materials can store the same amount of heating or cooling as water with up to 15% less volume. (Bradshaw, 2006)

Phase change materials are specially designed for a specific temperature range. This allows them to function to maintain the space temperature, but it also means they can only function

in that temperature range. If a few different temperature range controls are necessary, multiple materials will be needed.

Thermal Mass

Many early buildings relied on thermal mass to prevent the temperature of the building from fluctuating drastically on the inside. Materials like brick, concrete, and water, to name a few, are excellent thermal mass materials. The effectiveness of a thermal mass material depends on the ratio of the thermal capacitance (or heat capacity) of that material to the thermal capacitance of the air. When a material has a higher thermal capacitance to heat flow than air, most of the thermal energy will be stored in the material. This effect allows thermal mass to moderate the temperature within a space, maintain a comfortable temperature longer, and even out the midday peaks and nighttime lows for the interior spaces. (Bradshaw, 2006) Thermal mass can sometimes make the interior spaces feel uncomfortable. Combining thermal mass with radiant floor heating is common to mitigate these feelings. Another disadvantage is that some people find the materials unattractive.

Trombe Wall

Felix Trombe invented the Trombe wall system for space conditioning. The basic design of a Trombe wall is a thermal mass wall approximately 8 to 16 inches thick with a pane of glass 1 to 6 inches away from it placed on the sun side of the building, as shown in Figure 4-4. The concept behind a Trombe wall is that the sunlight passes through the glass pane and is trapped in the gap by the greenhouse effect. The thermal mass wall then heats up slowly, and blocks the direct solar gains. Then the wall radiates the heat into the living space slowly after the sun has set to moderate the temperature. The heating abilities of the Trombe wall can be extended by placing vents on the bottom and top of the wall. Natural

convection of the air being heated in the cavity will cause the air to rise and enter the living space through the top vent, while pulling cool room air in through the bottom vent. (Trombe Wall and Attached Sunspace, n.d.)

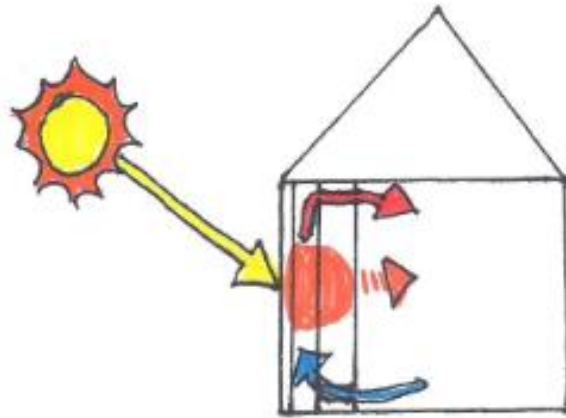


Figure 4-4. Simple diagram of a Trombe wall with vents in operation.

Trombe walls are simple passive systems, but they can only provide heating and there is minimal control over how that heat is delivered into the living space. They are also dependent on insolation, meaning they work better in warm regions, which is opposite of what is normally desired.

Solar Chimney

A Trombe wall can be turned into a solar chimney by adding a vent to the outside on the top, as shown in Figure 4-5. Solar chimneys are a method of providing passive cooling with only solar energy. The basic principal is the same, in that the hot air still rises, but now it “exhausts” out the top and pulls air out of the house. An additional vent can be added on the opposite side of the house and cooler air can be pulled into the house to replace the warm air. (Trombe Wall and Attached Sunspace, n.d.)

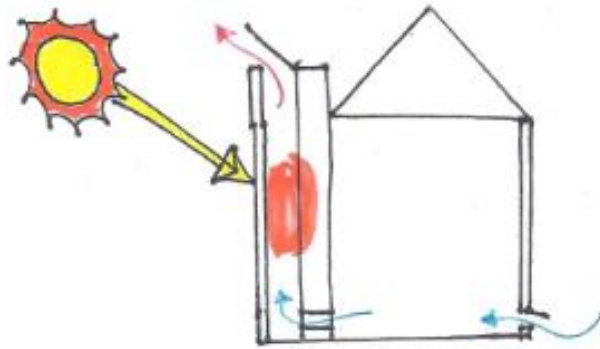


Figure 4-5. A modified Trombe wall design to make a solar chimney.

More traditionally, the solar chimney is a tall tower that is heated by the sun heating up the air inside of the “chimney” causing the rise of the hot air out of the space and pulling cooler air from another source. The solar chimney is actually a quite old architectural feature, often found in the Mediterranean. There are many buildings still standing today, where the solar chimney pulls cool air from an underground aqueduct, as shown in Figure 4-6. (It's Been Hot, 2008)

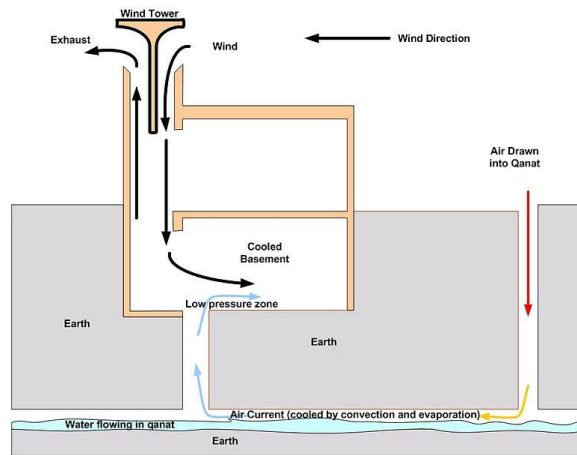


Figure 4-6. The basic design of a solar chimney found in many ancient Middle Eastern buildings. (It's Been Hot, 2008)

Solar chimneys are a simple passive system for cooling. However, they have the same issues as a Trombe wall; there is minimal control over the system and it relies on the solar heat to cause the circulation. An additional issue with solar chimneys is they need a place to pull cool air from. Good sources of cool air are subterranean and shaded sides of the building.

Thermal Roof Pond

Thermal ponds make use of the thermal mass properties of water to control the temperature in a space. They are located on the roof of a building as shown in Figure 4-7. The ponds have operable insulated covers. On hot days, the covers are left closed, and the water acts as a thermal mass, absorbing the heat from the conditioned space. At night the insulated covers are opened allowing the water to dump its stored heat into the night sky, so it is capable of reabsorbing heat the next day. During the heating season, the insulated cover is open during the day, and the water heats up with the sun. The covers are closed at night and the warm water radiates into the living space. (Indirect Gain Systems)

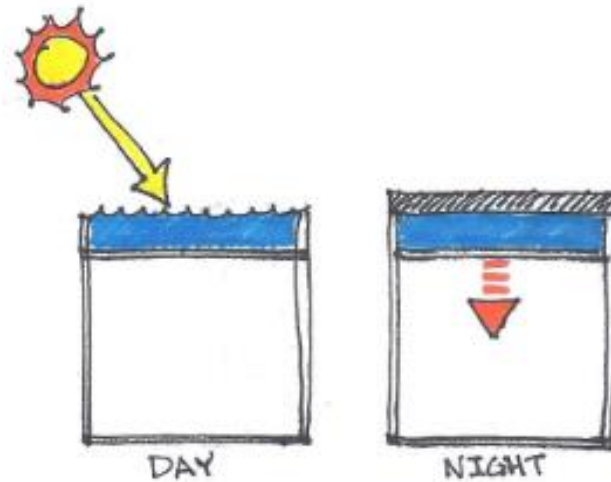


Figure 4-7. A basic example of heating-season operating procedure for a thermal roof pond.

Thermal roof ponds are capable of doing both heating and cooling passively, but the system is significantly more complex to actually accomplish both tasks. That added complexity comes with added expense. In particular, there are more concerns with a thermal pond in the structure and water sealing of the building. Roof-tops must be built to handle the increased weight of the pond, and the roof must be protected from potential water damage. Additionally, the system still relies on the solar heat to actually warm the interior spaces.

Insulation

Insulation is defined as a material that resists heat transfer, normally with a low thermal conductivity. Static air is actually one of the best thermal insulators, but because air is a fluid, it rises as it warms and becomes less dense. This circulation of air causes heat transfer by natural convection, which is extremely detrimental to thermal insulation of a space. In reality, the insulation normally installed into the building envelope, is designed to prevent the air in the space from moving. The effectiveness of an insulator is measured

with the R -value which is defined as the reciprocal of the overall heat transfer coefficient, U -value. The U -value is the rate of heat transfer, q , through a material per unit area and temperature difference, $U = q/(A DT)$. Thus, for one-dimensional conduction through a single layer of insulation where $q = k A (DT/L)$, k is thermal conductivity, and L is the insulation thickness. The R -value reduces to L/k . Therefore, the higher the R -value, or the lower the U -value, the better the insulator. Typical units for the R -value are either $\text{ft}^2 \cdot \text{F}/(\text{BTU}/\text{hr})$ or $\text{m}^2 \cdot \text{C}/\text{W}$.

Insulation comes in several forms, the traditional insulation is rolls or batts. These batts are laid into cavities built into the wall. A major issue with this type of insulation is that if it is squeezed or compressed it loses its ability to prevent air motion, and can sometimes become worse than just air in the wrong scenarios. Another issue with rolls of batting is they can be difficult to install in some spaces and then be left out.

The next evolution in insulation is “blown-in” insulation where the insulation material is distributed by a hose into the cavities required. This is often seen in attics. It is also a solution for filling harder to reach locations in walls. The weakness with blown-in insulation is the same as batting, in that if it is compressed or misapplied, it can be worse than no insulation.

Both batt insulation and blown-in insulation normally only fill the air gaps in the envelope. This means that the studs can cause thermal bridging from the exterior to the interior. Thermal bridging is when a material has a direct contact connection from the outside to the inside. Heat will travel on the path of least resistance. Resistance of a material is measured in terms of how long it takes for a BTU of energy to penetrate one square foot of material.

This number is dependent on the temperature differential on both sides of the material. Spray foam was developed to try to mitigate this heat transfer. It is similar to blown-in based on how it is installed, but it has a higher R -value per inch of thickness than traditional insulation materials, and it is sticky enough to be spread over the wooden studs, therefore causing a better thermal break from the outside to the inside of a space.

Green Roof/Wall

A green roof or wall is basically a roof or wall covered in plants. Green roofs and walls provide an additional layer of insulation to a building envelope. Additionally, they disrupt wind flow around a building, reducing the convective heat transfer, and they reduce the amount of direct solar gain on the building surface. For deeper soiled green roofs, the water suspended in the soil also acts as a thermal mass. Green roofs can also play a role in reducing the heat island effect.

The heat island effect is a term used to describe the phenomenon where urban environments are 2° - 10° F warmer than surrounding rural and suburban areas. This effect is caused by the high density of thermal energy storage materials, like concrete and asphalt, and the removal of vegetation. Vegetation reduces temperature in two major ways. First, tall plants, like trees, shade the ground and reduce direct solar gains on the surface. Second, plants perform evapo-transpiration. (Bradshaw, 2006) Evapo-transpiration is basically the cooling effect caused by the evaporation of water through vegetation and soil. By reintroducing vegetation with green walls and roofs, the amount of exposed thermal mass is reduced and evapo-transpiration increases. This keeps the buildings cooler. (Evapotranspiration - The Water Cycle, 2014)



Figure 4-8. A green roof in Portland, Oregon. (Green Roofs, 2013)

Some people find the plant life on the building aesthetically pleasing, although that advantage is debated. The major disadvantages of a green roof system is the increased maintenance and construction costs. Because of the requirement for a water barrier, soil, and plant life, the roof must be constructed to handle the increased loads of the green roof. Similar to the thermal roof pond, the roof must also have increased water barrier protection to prevent damage caused by watering the plants. The increased structural requirements mean the building will cost more to build.

Another disadvantage to a green roof is they normally require significant maintenance. The plants need to be maintained to not get out of hand. Depending on the variety of plant life, the building might need some form of irrigation system. This could cause the green roof to actually increase cost and water usage throughout the life of the building.

Cool Roof Material

Cool roof materials is very similar to green roofs in that their advantage is the reduction of the heat island effect. Normal, dark colored roofing materials absorb more solar energy

than lighter colored roof materials. This added heat causes the more direct solar gains on the envelope of the building, and therefore, more cooling load. In an attempt to reflect more of the direct solar gains, a roof of a lighter color is installed. The cool roof can be a light coating that is painted on top of the existing roof, or it can be light colored shingles.

The main issue with cool roof materials is aesthetic and cost. Many people find the light colored roof surface strange. They do make specialty shingles that are dark in color, but have a very high solar reflectance. These shingles tend to cost more than their light-colored counterparts.

V. SOLAR CAL POLY PLAN DESIGN PROCESS

Solar Cal Poly was notified that they are participating in the 2015 Solar Decathlon by the DOE in mid-February 2014. In an effort to encourage interdisciplinary cooperation, Solar Cal Poly coordinated with the Cal Poly Architecture department to run a series of classes that would help with the development of the architectural design and the submittals to the DOE for the various checkpoints in the competition. Each “design studio” would help shape the final house design for the decathlon. Other majors could join these classes to participate in the design portion of the project. The Mechanical engineering students participated in these design studios as technical advisors on passive design elements and HVAC considerations.

Spring Design Studio

The first design studio began at the end of March 2014. The studio analyzed the designs of previous solar decathlon houses, and looked at what made successful entries. The design studio was divided into small groups to design different house plans for a juried competition. On 2 May 2014, Ms. Willis presented the passive design considerations and design elements described in Chapter 5. For the remainder of the quarter, she attended several design studio meetings to answer technical questions about the various architectural designs being prepared for the design studio. Additionally, Ms. Willis participated in three architectural schematic reviews as a reviewer, where she questioned the preliminary architectural designs on their passive designs and mechanical considerations.

The juried competition was held in early June 2014. Each team presented their architectural design. The results of the juried competition were revealed on 10 June 2014.

Summer Design Studio

The summer design studio took the five selected designs from the spring design studio and began working on a parti to combine the best elements into a useable architectural design that would be submitted to the DOE in October for the schematic design review.

Additionally, the design studio began shaping the house to meet the desired characteristics of a prospective client in the Chumash Indian Tribe. Additional design elements included two bedrooms, and a master plan on his property near Santa Ynez. The introduction of a client steered the direction of the final summer design. Over the course of the summer design studio, Ms. Willis preformed several EnergyPro models to demonstrate how certain design decisions affected the thermal loads on the interior spaces.

The architectural team unveiled the final summer design floor plan, shown in Figure 5-1, in the middle of August. Based on the client's needs, the final design has two bedrooms, and views of the south vistas on the final site area. As can be seen in Figure 5-1, the house plan has a significant amount of southern glazing.

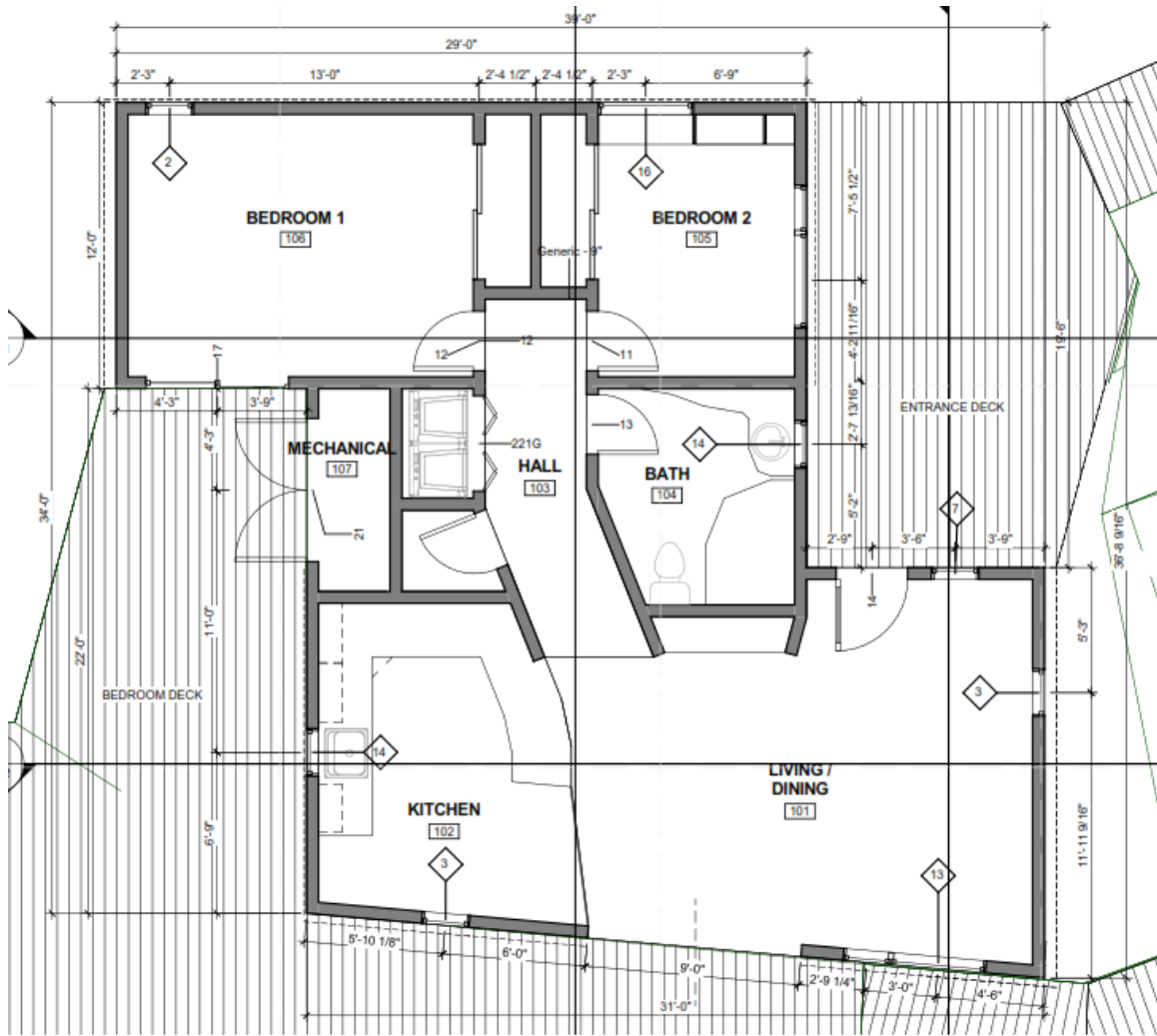


Figure 5-1. The final floor plan for the Solar Cal Poly entry from the summer design studio. (Poly, 2014)

The house design also contains a few interesting passive design elements. Use of SIP wall, floors, and ceilings produce a tight and thermally insulated house. A slatted exterior “wrap” shields the walls of the house from direct solar gains, therefore reducing the cooling loads within the space. A rendered image of the wrap is shown in Figure 5-2. This wrap also shades much of the glazing reducing direct solar gains.



Figure 5-2. A rendering of the Final Summer design showing the slatted shade elements. (Poly, 2014)

Figure 5-3 shows a section view of the wrap element.

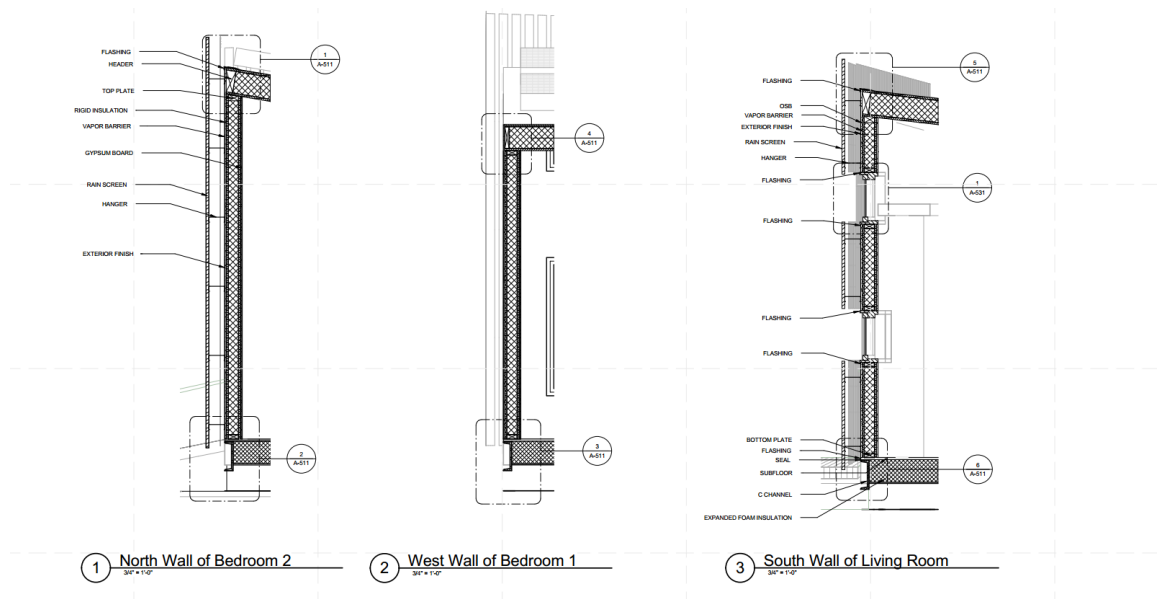


Figure 5-3. A section view of the slatted wrap element in the final summer design from the 9 October 2014 DOE design submittal. (Poly, 2014)

Additionally, the final design has approximately 30% glazing to floor area, and only used small east and west facing windows. The plans call for double-pane windows with non-metal frames to try to minimize the thermal bridging into the interior space.

The final summer design studio plan was completed in mid-August 2014. Ms. Willis and the engineering team then worked on finishing the design for the DOE design submittal due 9 October 2014. Ms. Willis performed the thermal load analysis, HVAC plan, and assisted with the dedicated exhaust ventilation system on the final summer design studio floor plan.

Fall Design Studio

After the DOE Design submittal was completed on 9 October 2014, the architecture team rolled out their new floor plan, shown in Figure 5-4. Due to time constraints, the remainder of this report will focus on the energy modeling and HVAC design used in the 9 October DOE submittal. The remainder of this report goes through the thermal load modeling and HVAC design process for the Solar Cal Poly mechanical engineering team. The Solar Cal Poly team should use the remainder of this report as a guide on the basic process.

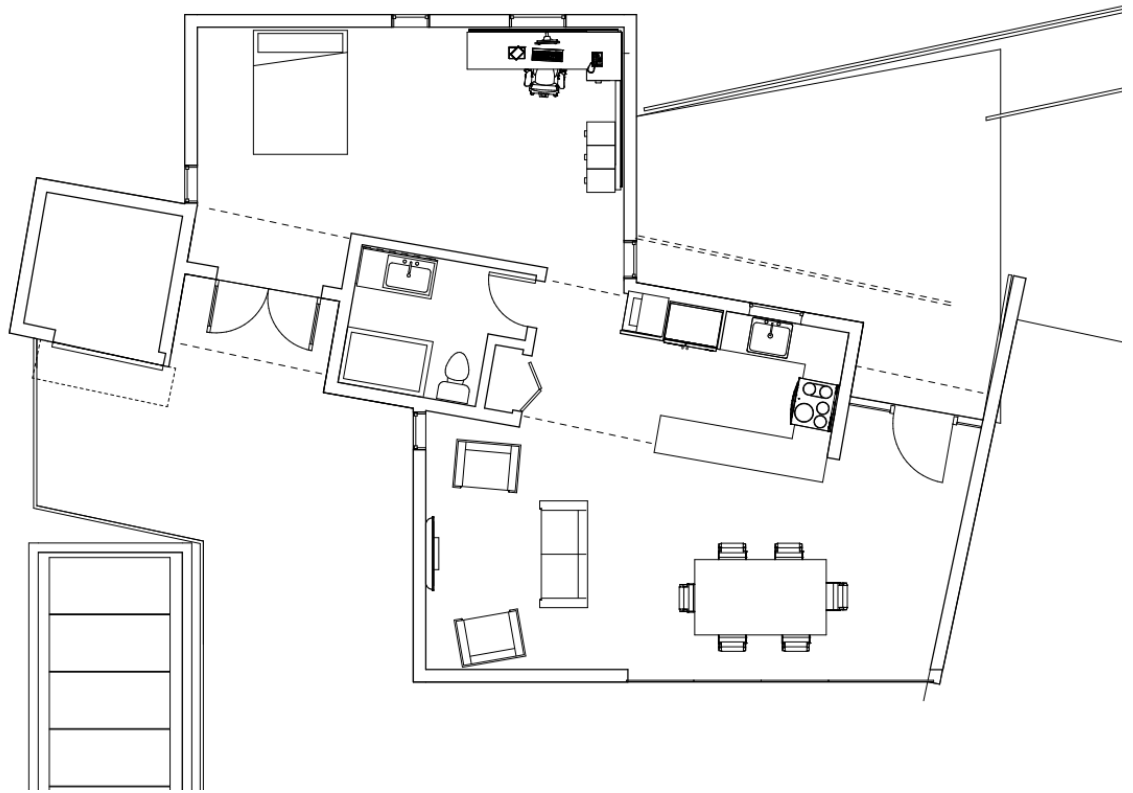


Figure 5-4. The Fall Studio Design rolled out this floor plan after the October 9th DOE submittal. (Poly, 2014)

VI. ENERGY LOAD MODELING

It is important to properly size HVAC equipment. If the system is under-sized, it will not adequately condition the interior spaces. This is especially important for the solar decathlon competition, where the house must maintain an indoor air temperature (IAT) of 71°F through 76°F for the duration of the competition. This is a very tight margin, and normally not recommended for energy efficiency. In general, a home is only occupied in the morning and evenings during the work week. In those unoccupied times an intelligent homeowner would “setup” or “setback” the thermostat to reduce energy usage during the peak of the day. Additionally, allowing the IAT to drop at night while the occupants are asleep in bed, saves energy.

For the opposite situation, oversizing HVAC equipment can be worse for energy efficiency and comfort. For obvious reasons, oversized equipment uses more energy than necessary on startup, so if a system is significantly larger than what was necessary it uses more energy than necessary. This is definitely a concern for the solar decathlon competition, as the energy budget is tightly controlled due to the limitations of the PV systems. Additionally, oversized HVAC equipment can “short-cycle” which causes comfort issues within the conditioned space. This is because even without thermal mass, it takes more time for the object within a space to reach a certain temperature than it takes for the air to reach a certain temperature. When an HVAC system is too large, it can alter the temperature of the air quickly enough that the thermostat thinks the room has reached set point. In response, the equipment shuts off, but because the walls, floors, and furniture didn’t have enough time to absorb the energy and change temperature the room quickly returns to the previous temperature. Once the air temperature drops outside the set-point, the HVAC equipment

kicks back on again. The constant starting and stopping of the equipment, shortens the usable life of the equipment and wastes energy. Additionally, people often find the spaces uncomfortable as the room never actually stays at the desired set point.

It is obvious that a properly sized HVAC system would provide the required space conditioning with the smallest amount of capital costs and the most amount of comfort. Proper sizing of HVAC equipment relies on exactly how much heating and cooling the house will need to maintain the desired set point. There are many computer programs and methodologies to solve for the proper thermal load sizing. In the case of the Solar Cal Poly entry, the system must be able to maintain the desired set point using as little electricity as possible. Several different methods and computer modeling programs were used to find the required heating and cooling loads of the house design. These different methods were compared to confirm the accuracy of the model, and make sure that the smallest possible system would be installed in the Solar Cal Poly competition house.

CBECC RES

California Building Energy Code Compliance (CBECC-Res) software is a free government-made program to assist with code compliance calculation requirements in California's Title 24 (T-24) energy efficiency codes. The newest California code cycle went into effect in July 2013, and with that code cycle this program was released as the foundation for all approved T-24 compliance software. This was the obvious first choice, as the software was free and would show house compliance under the new, more strict energy codes.

The plan was to use CBECC-Res to demonstrate how changes in the floor plan affected the overall loads quickly for making plan decision. The floor plan details are entered into the program, and heating and sensible load output was recorded and analyzed. Unfortunately, the CBECC-Res program was rolled out with a lot of key features still undeveloped, a significant numbers of errors, and an almost unusable error alert system. It became clear that this CBECC-Res program was not going to be usable for quick plan comparisons.

EnergyPro

EnergyPro, developed by Energy Soft, LLC, is a well-established building modeling software often used for compliance calculations in California. EnergyPro 6 is the latest release and it is an approved compliance calculator for the 2013 California T-24. As an approved compliance calculator, EnergyPro6 is required to use the CBECC-Res base program to perform its load calculations. It was decided to use EnergyPro 5 which is only valid for 2008 California T-24 energy code compliance. Since EnergyPro 5 has been in operation for the last five years, many of the early program problems have been resolved.

EnergyPro 5 uses a similar layout to CBECC-Res. The floor plan details are entered into the program tree, and then the program provides heating and sensible loads. Unlike CBECC-Res, EnergyPro 5 provided quick load results that were used to demonstrate how floor plan changes affected the room loading.

EnergyPro 5 program has some limitations. The program does not take into account wall shading, like the slats on the summer final design. Additionally, since the wall, glazing, and door surface area is entered based on direction, the program does not take in account

the interactions between the envelope. EnergyPro 5 works well for quickly comparing several potential floor plans, but is insufficient for final detailed load analysis.

DesignBuilder

Once a floor plan was settled on for the Solar Cal Poly house design, a model of the house was created in DesignBuilder, developed by DesignBuilder Software, Ltd. DesignBuilder shows the load requirements for all the rooms within the building for various times of the year. This allows a more detailed model that can be used to layout an HVAC system to properly and more efficiently deliver that required conditioning to the individual spaces.

DesignBuilder uses the EnergyPlus modeling engine produced by the U. S. Department of Energy (DOE). EnergyPlus performs energy analysis similar to EnergyPro and CBECC-Res to simulate the heating and cooling loads necessary to maintain a set point, but it allows for a much more detailed analysis because it accounts for many more construction parameters. Thus, results are based on the user's detailed description of the building and location. Additionally, specific wall assemblies can be created in the program and used in the model. This allows one method of finding energy savings from the slatted house wrap in the final summer design. These wall assemblies will also allow a method for looking at the effectiveness of phase change materials.

The EnergyPlus program uses several program modules to perform the calculations. Brief descriptions of the various modules summarize how the programs model the energy required for heating and cooling. The EnergyPlus *Simulation Manager* communicates with the DesignBuilder Integrated Solution Manager (ISM). The ISM can be divided into three sub-managers that communicate with the remaining modules, Surface Heat Balance

Manager, Air Heat Balance Manager, and Building Systems Simulation Manager. The Surface Heat Balance Manager communicates with the following five modules: *Sky Model Air*, *Shading*, *Daylighting*, *Window Glass*, and *Conduction Transfer Function (CTF) Calculation*. The Air Heat Balance Manager communicates only with the *AirFlow Network Module*. Finally, the Building System Simulation Manager has two major modules: *Air Loop* and *Zone Equipment* (EnergyPlus Engineering Reference, 2014). A diagram of how the modules interact is shown in Figure 6-1.

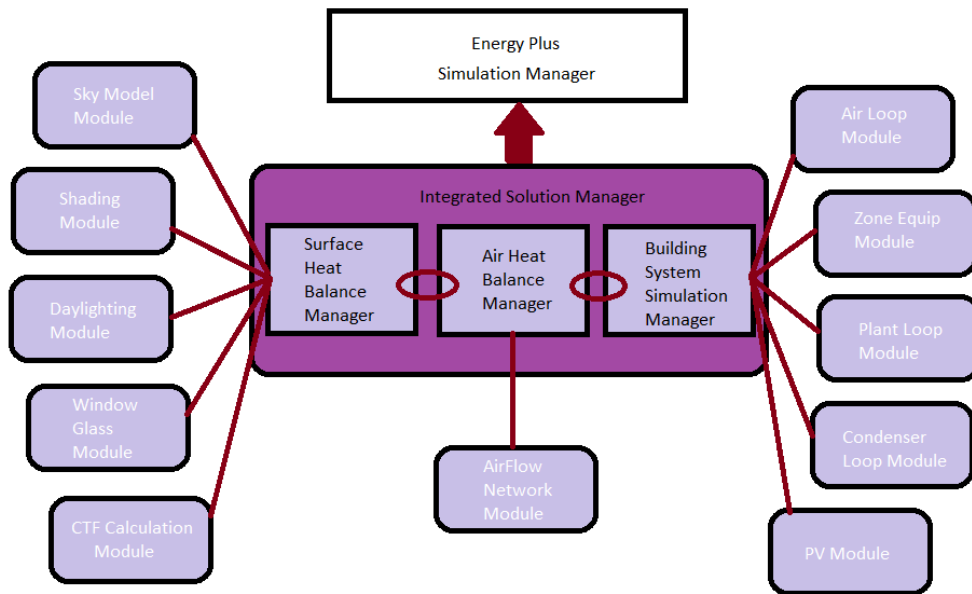


Figure 6-1. A diagram of the calculation methodology used by EnergyPlus and DesignBuilder.

The three sub-managers are solved simultaneously to account for the complex interactions between the supply and demand sides of the heating and cooling loads. The solution relies on the Gauss-Seidel method of successive substitution iteration to obtain convergence. The Surface Heat Balance Manager is integrated to the Air Heat Balance Manager by a series

of ordinary differential equations (ODEs) that are solved simultaneously with the predictor-corrector approach. For example, a heat balance is done on a zone. The heat balance is dependent on the internal convective loads, the convective heat transfer from the zone surfaces, infiltration of outdoor air, inter-zone air mixing, the energy stored in the zone air, and the air system output. Assuming the mass flow rate of air into the zone is equivalent to the mass flow rate out of the zone, and that the temperature of the exiting air is equivalent to the mean air temperature of the zone, the change in the energy stored in the zone is equivalent to the sum of the air system output and the rest of the zone loads. The heat balance equation used is shown below:

$$C_s \frac{dT_z}{dt} = \sum_{i=1}^{N_{sl}} \dot{Q}_i + \sum_{i=1}^{N_{surfaces}} h_i A_i (T_{si} - T_z) + \sum_{i=1}^{N_{zones}} \dot{m}_i C_p (T_{zi} - T_z) + \dot{m}_i C_p (T_\infty - T_z) + \dot{Q}_{sys}$$

Where:

$$\sum_{i=1}^{N_{sl}} \dot{Q}_i = \text{sum of the convective internal loads}$$

$$\sum_{i=1}^{N_{surfaces}} h_i A_i (T_{si} - T_z)$$

= convective heat transfer from the zone surface

$$\sum_{i=1}^{N_{zones}} \dot{m}_i C_p (T_{zi} - T_z) = \text{heat transfer due to interzone air mixing}$$

$$\dot{m}_{inf} C_p (T_\infty - T_z) = \text{heat transfer due to infiltration of outside air}$$

$\dot{Q}_{sys} = \text{air systems output}$

$C_z \frac{dT_z}{dt} = \text{energy stored in zone air}$

$C_z = \rho_{air} C_p C_T$

$\rho_{air} = \text{zone air density}$

$C_p = \text{zone air specific heat}$

$C_T = \text{sensible heat capacity multiplier}$

The remainder of this section discusses individual modules and EnergyPlus' built-in economics calculations.

Surface Heat Balance Manager

The purpose of the Surface Heat Balance Manager is to solve for the change in temperature within the zones. Several modules solve for the various subcomponents that the Surface Heat Balance Manager requires to solve for zone heating and cooling loads.

Climate Calculations

The weather files used in DesignBuider have hourly and sub-hourly climate data for a specific site. These files contain a key amount of data that is required for the following modules to function. The specific data provided can vary from site to site, but in general weather files contain the following information: dry-bulb temperatures, dew-point temperature, relative humidity, barometric pressure, direct normal solar radiation, diffuse

horizontal solar radiation, total sky cover, opaque sky cover, wind direction, and wind speed.

Often only high and low dry-bulb temperatures are recorded for any particular day. To model temperatures hourly or sub-hourly a multiplier is applied to the dry-bulb data based on the time-step. The specific multipliers used in EnergyPlus are found in ASHRAE 2009 HOF Table 6 pg. 14.11. This multiplier makes the weather fit a standard temperature curve for a typical day. The highest temperature is at 3:00 p.m., and the lowest temperature is at 5:00 a.m. ASHRAE has also shown that wet-bulb temperature also follows the same pattern on a typical day, so the same model can be used to model humidity.

Sky Module

In short, the sky module calculates the position of the sun, and how much illumination the sun is providing over a desired time period. This information helps with the shading calculations and also is a major contributor to the calculated cooling loads, as solar gains through glazing is the largest contributor to heat gain in a home.

Sky Radiance Model

There are three models commonly used to calculate solar radiance: ASHRAE Clear Sky Solar Model, TAU model (revised ASHRAE clear sky model), and Perez Direct/Diffuse Splitting Method. Solar radiance is the amount of solar radiation on a surface. The default model in EnergyPlus is ASHRAE Clear Sky Solar Model. This model is valid only for US or other Northern Hemisphere Temperate Climates. Weather files normally have a solar radiance interpolation of average values over an hour that can be used.

Sky radiation is an important value in solar collector calculations. Simply, sky radiance is a measure of how much radiant energy is exchanged between the sky and the ground. When modeled, the sky and ground are often treated as flat plates, and the sky is considered a black body radiating at a uniform temperature. (Beckman, Solar Engineering of Thermal Processes, 2006) EnergyPro actually uses an empirical model based on measurements taken by Perez et al. in 1990 (The Board of Trustees of the University of Illinois & Ernest Orlando Lawrence Berkely National Labratory, 2014). The Perez model relies on the superposition of three distributions: isotropic distribution of the domed sky, circumsolar brightening, and horizon brightening. For short-wave radiation, the isotropic distribution depends on the clearness factor and brightness factor from the weather file. Circumsolar brightening assumes the strongest point is the location of the sun at that time-step. Horizon brightening assume it is a linear source at the horizon, and independent of azimuth. For sky long-wave radiation, EnergyPlus assumes the radiance distribution is isotropic. Any obstructions and the ground are assumed to be at outside air temperature and have an emissivity of 0.9 (the ratio of the emitted power and the emitted power of a blackbody at the same temperature).

Shading Module

The Shading Module takes the sky radiation information calculated by the Sky Radiance Module and compares it to the geometry of the building. Shading does the opposite of the solar radiation. Shading is a section of envelope not receiving short-wave or long-wave radiation. This information will affect the heat transfer through the envelope, thus reducing the cooling loads within the zones.

Solar Position

The first piece of information required to calculate shading is solar position. Generally solar position is described in three directional cosines: solar hour angle (H), solar altitude angle (β), and solar azimuth angle (ϕ). The solar hour angle gives the “solar time” which is the time according to the position of the sun. For example, solar noon is the time where the sun is at its zenith. This time does not always coincide with the actual time, noon. On this scale, solar noon is considered an hour angle of zero.

$$H_{noon} = 0^{\circ}$$

Before noon is considered positive, and afternoon is negative. An hour is equivalent to 15° of a solar hour angle. Solar altitude angle is the angle from the horizontal, where higher off the ground is treated as positive. Solar azimuth angle is the angle of the sun in the sky where North is considered zero, clockwise is positive. Both angles are in degrees, solar altitude remains between 0° and 90° , and solar azimuth angle is 0° at due South, due East is -90° , and due West is $+90^{\circ}$.

Surface Geometry

In DesignBuilder, the desired building is described in a three-dimensional Cartesian coordinate system. Using the Cartesian system allows a simple way to define the geometry of the building. This geometry is then compared to the solar position, to find where shadows are falling on the exterior surface. In DesignBuilder, North is defined as the positive X -direction. There is also an arrow for clarification. It is important to define North in the proper orientation of the building or the shading and solar position modules will give erroneous heating and cooling loads.

Solar Gains

The solar gains on a specific surface are dependent on the material properties of the surface, the solar radiation on the surface, the percentage of the area protected from solar radiation (shaded), and the angle between the surface and the radiation source. The solar gains calculated are related to the zone temperature with other modules of the Surface Heat Balance Manager.

Daylighting Module

Daylighting gives an idea of how much solar illuminance, or light, enters the zone through glazing, and also can find how much electric lighting will be needed to reach a certain luminance within the zone. This module interacts with the Solar Radiance and Shading modules to generate daylighting factors: ratio of interior illuminance to exterior horizontal illuminance, sky luminance distribution, window size, orientation, glazing illuminance. These factors are calculated based on hourly sun positions. These factors reset to zero at sunrise and sunset to prevent spikes caused by the sun having a solar altitude angle of $\pm 90^\circ$ at those times. EnergyPlus can use four sky types for calculating illuminance: clear, clear turbid, intermediate, and overcast.

The daylighting calculation takes the previous heat balance calculated at the previous time-step, and calculates the next set of illuminance by interpolating the previous daylighting factors and multiplying by horizontal illuminance. Additionally, EnergyPlus can compensate for glare and high solar gains by deploying operable shading elements. This is not by default, and must be set up in DesignBuilder. After the illuminance is calculated, EnergyPlus can then find the amount of electric lighting required to meet the set illuminance needs in the zone.

Window Glass Module

EnergyPlus can model glazing, or windows, layer-by-layer or by converting to an equivalent single layer. For the layer-by-layer method several components are needed to fully assemble a window. Glazing is by far the most important aspect of a window. Normally it is the largest portion, has the greatest effect on the energy transfer, and is literally the crucial component that defines a window. The transmittance (τ) is the percentage of radiation that is allowed to pass through the glazing into the conditioned zone. This is often indicated by the solar heat gain coefficient (SHGC) that can include the fraction of incident solar radiation that is directly transmitted or that is absorbed and reradiated. The higher the SHGC the easier it is for solar radiation to pass either directly or indirectly through the window, and the more cooling load is required.

Two other required properties of glazing for a layer-by-layer model are front reflectance and back reflectance. Front reflectance refers to the reflective capability of the outside surface of the glazing, the part normally exposed to direct solar radiation. The back reflectance is the reflective capability of the inside surface of the glazing. Reflectance is the measure of how much radiation is reflected off the surface.

If there is more than one layer of glazing, there will be a gap. This gap is filled with a gas, such as air or argon. Gases like air are good insulators, so they increase the thermal resistance of the assembly without reducing the visibility. The frame and dividers are used to hold the glazing together. They can be made of metal, wood, or plastic. The glazing, gap, and frame have varying levels or resistance to heat transfer. This resistance is often measured in R -values or U -factors as defined earlier.

Finally, shading elements like drapery, shades, and blinds, reduce the solar heat gain and glare within the conditioned zone. With all these elements layered together and placed in the DesignBuider model, EnergyPlus can fairly accurately model the heating and cooling loads caused by the windows.

The combined method is significantly easier and faster than the layer-by-layer method. In many modeling cases, the windows are already selected and those windows have a defined U -factor and SHGC. In other cases, the exact design of the windows is unknown, but the maximum values of U -factor and SHGC have been determined. In these cases the combined method is a better choice. Basically the U -factor and SHGC are entered in for the desired window area, and EnergyPlus treats it like a single layer with those properties. This method is much faster to calculate and produces reasonably good calculations of the heating and cooling loads. It is important to note that the values from the “simple” model should not be applied directly into the layer-by-layer method. These methods use a slightly different methodology, and the numbers will not be consistent.

Conduction Transfer Function Calculation Module

The conduction transfer function calculation (CTF) module calculates the transfer of heat conducted through solid surfaces, like walls, roofs, and floors. CTF uses a state space technique to solve for the heat fluxes as a function of just environmental temperatures.

CTF analysis requires the structure and properties of the envelope be defined. Most users elect to define their materials with four parameters: thickness, conductivity, density, and specific heat. The materials are then assembled into a “construction” piece. For example a wall might have five layers, interior gypsum board finish, wood studs 16” O.C., R-13

rolled batt fiberglass insulation, vapor barrier, and exterior wood siding. EnergyPlus divides these material layers into 6-18 nodes to apply the state-space method. Multi-layer constructions also have interface nodes (half node in first layer and half node in second).

Sometimes, a layer needs to not affect the thermal mass properties of the construction model. In these cases a “no mass” only R -value can be used. If the inner or outer layer of a construction assembly is a “no mass” material, EnergyPlus converts the properties of this layer to the properties of air with the thickness adjusted to maintain the users desired R -value. For “no mass” layers found in the middle of a construction assembly, the layer is treated as a single node with a specific resistance where the density and heat capacity are set to zero.

Conduction Finite Difference Solution Algorithm

There are some situations where the state space method used above is not accurate. An obvious example is phase change and other variable thermal conductivity materials. In these cases, EnergyPlus has two methods for solving these conduction problems. The first method is a semi-implicit method called the Crank-Nicholson scheme where the space discretization constant can be set by the user. EnergyPlus uses the default discretization constant of 3, where lower numbers result in more nodes and higher numbers yield less nodes. The Gauss-Seidel iteration scheme calculates temperature at various nodes simultaneously and the relaxation coefficient is used to increase stability. In EnergyPro, this method is limited to thirty iterations or when the temperature change at successive iterations is less than 10^{-6} °C. Most conventional material calculations converge in three iterations. PCM normally takes 2-3 more iterations.

In addition to the previous thermal model for construction assemblies, EnergyPlus uses a separate outer iteration loop on inside surfaces to account for internal long-wave radiation exchange. This calculation has a maximum of 100 iterations or temperature change of less than or equal to 0.002°C in successive iterations. During this calculation, node enthalpies updated each iteration are used to develop the overall heat capacitance (C_p) and thermal conductivity of the material.

CTF works well in this scenario, because the interior fluxes and temperatures do not need to be solved. But because of rounding and truncation errors, CTF can become unstable at very small time steps. This is most apparent for thermal mass and other structures with long characteristic times. To mitigate this effect, EnergyPlus uses a minimum time step of a half hour, and recommends no smaller than one hour time steps when modeling buildings with thermal mass elements.

Outside Surface Heat Balance

The outside surface of a building has other factors that need to be taken into account. Heat balances on outside faces include (1) absorbed direct and diffuse solar (short-wave) radiation from the sun, (2) long wave thermal radiation exchange with the surroundings, (3) convective thermal energy exchange with the outside air, and (4) conduction thermal energy transport through the wall. External short-wave radiation is based on the location of the surface, the angle of incidence, surface material properties, and weather conditions. External long-wave radiation is the net radiation exchange between the surface, sky, and ground. The factors that determine the net long-wave radiation absorption by the surface are the surface absorptivity, surface temperature, sky and ground temperatures, and sky and ground view factors. In EnergyPlus, each surface emits or reflects diffusely and is

considered grey and opaque. The surface is treated like it is at a uniform temperature. The sky and ground are also assumed to be at a uniform temperature that is the same as the air. But, the air is considered not participating with regards to radiation exchange, thus the radiation exchange is modeled as only a surface-to-surface problem. Energy flux leaving the surface is modeled as evenly distributed across the surface. With these assumptions, the Stefan-Boltzmann law is used to calculate the long-wave radiative heat flux components on the exterior surface.

Convection on the exterior surface is the last type of heat transfer that needs to be considered. There are several methods that can be used to calculate the convection coefficient: Simple Combined, TARP, moWiTT, DOE-2, and the adaptive convection algorithm. (The Board of Trustees of the University of Illinois & Ernest Orlando Lawrence Berkely National Laboratory, 2014)

Inside Heat Balance

To properly model the heat transfer through a surface, the interior conditions must also be considered. In EnergyPlus, the interior heat balance is modeled with four coupled heat transfer components: (1) conduction through a building element, (2) convection to air, (3) short-wavelength radiation absorption and reflection, and (4) long-wavelength radiation exchange. The heat balance of the interior surface is shown below:

$$q_{LWX}'' + q_{SW}'' + q_{LWS}'' + q_{ki}'' + q_{sol}'' + q_{conv}'' = 0$$

Where:

$q_{LWX}'' = \text{Net longwave radiant exchange flux between zone surfaces}$

$q_{sw}'' = \text{Net short wave radiation flux to surface from lights}$

$q_{LWS}'' = \text{Longwave radiation flux from equipment in zone}$

$q_{ki}'' = \text{Conduction flux through the wall}$

$q_{sol}'' = \text{Tranmitted solar radiation flux absorbed at surface}$

$q_{conv}'' = \text{Convective heat flux to zone air}$

The interior short-wavelength radiation comes from solar radiation entering the zone through windows. Long-wavelength radiation comes from absorption and emittance of low temperature radiation sources (some examples are zone surfaces, equipment, and people.) These interior radiation sources are considered grey, diffuse, and interchangeable. EnergyPlus treats the interior zone air as completely transparent to long-wavelength radiation. This simplifies the equation by allowing the convection model to be separate from the radiation model. This assumption is reasonable because the water vapor concentration tends to be low in conditioned spaces.

The air temperature inside the interior zones are considered “well-stirred”, and therefore the interior air temperature is uniform. Internal mass surface, surfaces connecting one internal zone to other internal zones, are considered adiabatic and the interior temperature is the same on both sides of the construction. If there is a concern about the interaction between two interior zones, two mass sections need to be put in to calculate the heat transfer between the zones.

Air Heat Balance Manager

The purpose of the Air Heat Balance Manager is to connect the heating and cooling loads from the Surface Heat Balance Manager to the Building System Simulation Manager. This is basically done by balancing the airflow from the building systems with the load requirements of the zone predicted by the Surface Heat Balance Manager.

AirFlow Network Module

The Air Heat Balance Manager just has one support module, the AirFlow Network Module. This module works with the ventilation throughout the building. EnergyPlus assumes that all the air coming into the zone is equal to the air leaving the zone. The uncertainty in this section of the model is the infiltration rate. Infiltration is when air leaks into the conditioned zone, or out of the conditioned zone through cracks, opening doors, leaky windows, and any number of other places. EnergyPlus has made several assumptions to deal with the infiltration of the air system. First of all, the infiltration air is considered to be immediately mixed well with the zone air. EnergyPlus defaults to the assumption that the infiltration rate is constant at all hours. There is evidence to show that infiltration will vary depending on the time of day and weather conditions, but at this point, the model treats infiltration as a constant rate of a set air changes per hour (ach). DesignBuilder has this value default set to 0.7 ach.

Building System Simulation Manager

The final manager in the EnergyPlus model deals with the active HVAC equipment. In DesignBuilder, the “standard” model option uses default values for this section. It is very useful for buildings that do not have a set HVAC system yet. The model option “Detailed HVAC” allows inputs for the HVAC system. This model increases the complexity of the

model, so it should only be used after an HVAC system is basically designed. The Building System Manager can be divided into two basic modules, the Air-Loop Module and the Zone Equip Module.

Air Loop Module

The Air Loop Module can be divided into two sub-loops, the primary air-side and the zone equipment side. The primary air loop can also be thought of like the supply side loop. It is responsible for the supply fans, return fans, economizers, and the cooling/heating coils. The zone equipment loop can be called the demand side. It contains the components that would be located in the zone, or at least would be responsible for the direct delivery of the conditioned air. Some systems are air terminals, fan coils, baseboards, window air conditioners, and plenums.

The air loop is a steady state model that uses a system of coupled algebraic equations to balance the combined energy and mass flow. Because of this an iterative solution method is required. In general, the zone equipment sets the flow rates, then the primary air side provides cooled air flow rates and then calculates the resulting temperature. Humidity and mass flow rates are major variables in this calculation.

Zone Equipment Module

The Zone Equipment Module can store actual equipment data to better model a building's usage or it can calculate initial specifications based on an initial calculation of the load variables from the Surface Heat Balance Manager. The design zone air flow rate is calculated and stored for auto sizing. Therefore, all the zone equipment can be simulated. The equipment information is then transferred from the outlet node to the inlet node of the

air system. This simulates the return air of the system and allows the module to iterate to convergence.

Economics Calculations

DesignBuilder and EnergyPlus also have economics modules that can calculate approximate costing. There are three methods for performing calculations. The simplest method is a line item list. All the components and their respective costs are summed up for a total cost. The adjusted method is basically the simple line item method, but an adjustment fee is added on to compensate for profit margin and design time. Finally, the final cost for the house can be compared to the cost of a “reference” house. This allows for a quick comparison and for cost-benefit analysis.

The economics calculator has several other features including Life-cycle cost analysis, expressing cost in terms of cash flow, net present value, taxes and depreciation calculations. These tools could be very helpful for many different aspects of the Solar Decathlon project and industry endeavors.

VII. Design Builder Energy Model Results

First, base model of the floor plan was created in DesignBuilder. The three-dimensional model of the final summer design floor plan is shown in Figure 7-1.

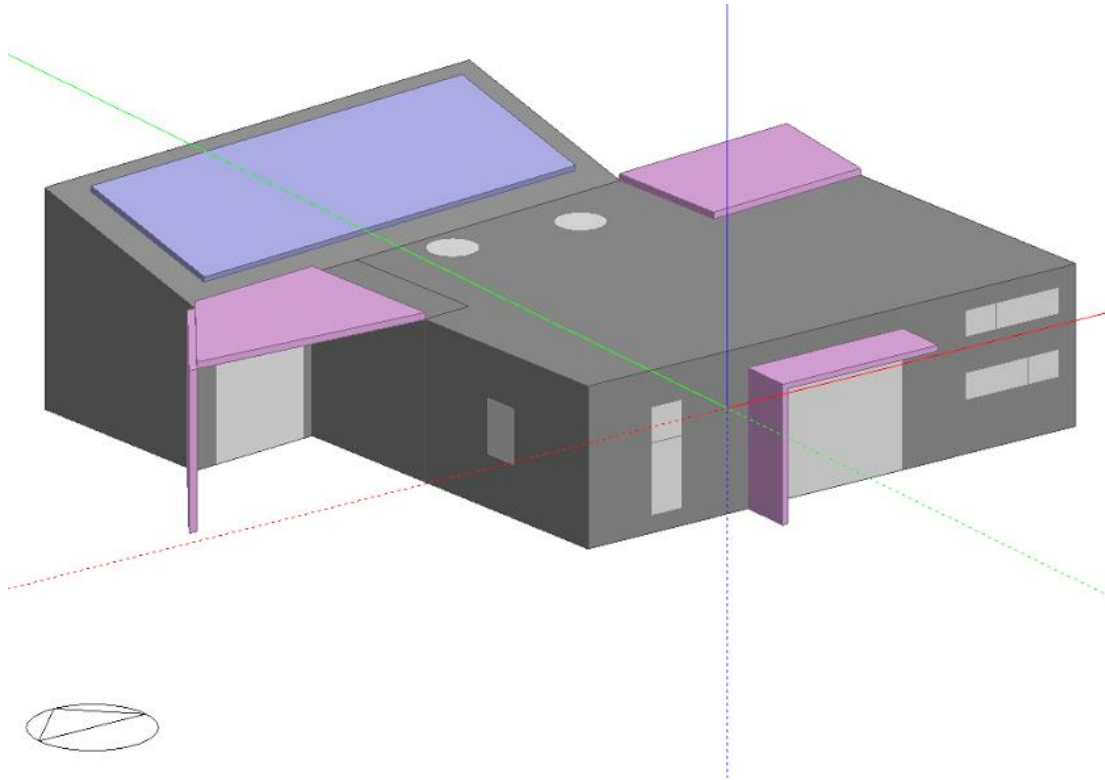


Figure 7-1. The three-dimensional model of final summer floor plan created in DesignBuilder.

The house was created with 6-inch structurally insulated panel (SIP) walls. The roof was modeled as a conventional roof with a cool roof coating. The infiltration was set to 0.5 air changes per hour (ach) while natural ventilation was set to 3.0 ach. An air change per hour is how many times all the air in the space is replaced with new air per hour. So if a zone has a volume of 1,000 ft³ and an infiltration rate of 3.0 ach, then 3,000 ft³ of air cycles through the zone in an hour, or a flow rate of 50 cubic feet per minute (cfm). Because of

the Solar Decathlon's tight temperature margin, the occupancy sensor was setup to operate the HVAC systems all day to keep a set point of 73⁰F.

The building heating and cooling loads were run twice, once exactly as described above, and another time with an addition of a 4-inch air gap in the wall construction unit. The air gap represents the gap between the exterior walls and the slatted house wrap. The goal was to see how much energy load savings would be received from a building both with and without a slatted wrap.

The house wrap should prevent direct solar gains on the exterior surface which will dramatically reduce the solar heat gain through the surface, but natural convection through the air gap should also produce some cooling. This method of modeling the house wrap does not reduce the solar heat gains on the surfaces, it just insulates the building more so less heat is able to conduct through the surface.

A few other attempts were made in Design Builder to try to model the house wrap. One attempt tried to use component blocks to assemble a physical wrap around the house. This method was extremely unwieldy, and the resulting component wrap was inaccurate. It was difficult to maintain the same thickness, distance from the house, and shape. Another method attempted was to upload the architecture Revit model directly into DesignBuilder. Theoretically, this should have worked, but the program is not the easiest to work with. Basically, if even one reference point on the Revit house model is off or duplicated, it can cause errors that make it almost impossible to work with the file and get any usable data. In this specific case, the cooling load nearly doubled with this method. It was decided that

finding the savings from only the insulating nature of the air gap would give at least a qualitative and order of magnitude estimate on what kind of savings the measure will cause.

The heating and cooling loads for the competition week separated by space type are summarized in Table 7-1.

Table 7-1. A summary of the heating and cooling model results comparing the more conventional house design with a house with a full wrap around the exterior for the 2015 competition week in 2015.

	Steady State Heat Loss (kBTU/h)		Total Cooling Load (kBTU/h)	
	w/o Wrap	w/ Wrap	w/o Wrap	w/ Wrap
Library-Bed	5.26	4.00	1.60	1.50
Master Bed	7.21	5.53	2.40	2.30
Common Zone	19.27	14.80	11.50	11.20
Bathroom	2.98	2.36	1.20	1.10

The savings is minor for the wrap when it comes to cooling load, but actually significant when it come to the steady-state heat loss. The results make sense due to the increase insulation of the assembly, and not the decrease in solar heat gains. It is clear that a 2-ton condenser will meet the cooling requirements of the home.

Once the assumptions and set-points for the final design studio were entered into DesignBuilder, a simulation of a year was run to see if the building could meet the temperature and humidity requirements of the competition year around. The data was analyzed as shown in Figure 7-2, the causes of the heating and cooling loads for October 1st are estimated based on a typical meteorological year (TMY) or average semi-hourly temperature. October 1st was selected for this chart because it is the day in the middle of the actual 2015 Solar Decathlon completion. The green, blue, and red lines represent the

heat energy added to the system due to lighting, computers, and people in the zone, respectively. The orange and dark blue lines represents the added heat or the heat removed from the zone by the HVAC equipment, respectively. The grey line shows the heat added to the system by solar gains through the windows and walls.

Based on this model, the final summer design does not require heating during this design week. The most significant load on the interior spaces is solar gains on the exterior. There is a small increase in solar gains in the early morning, this is probably due to the glazing on the eastern side of the building. The solar gains spikes further at approximately 10:00 a.m. when the sun aligns with the large southern glass door. The solar gains drop off quickly from approximately 12:30 p.m. till sunset, due to the significant western shading elements in the design and the minimal amount of western glazing. The zone sensible cooling load peaks at approximately 3:00 p.m. when the outdoor air temperature tends to be highest. The remainder of the thermal loads are fairly insignificant.

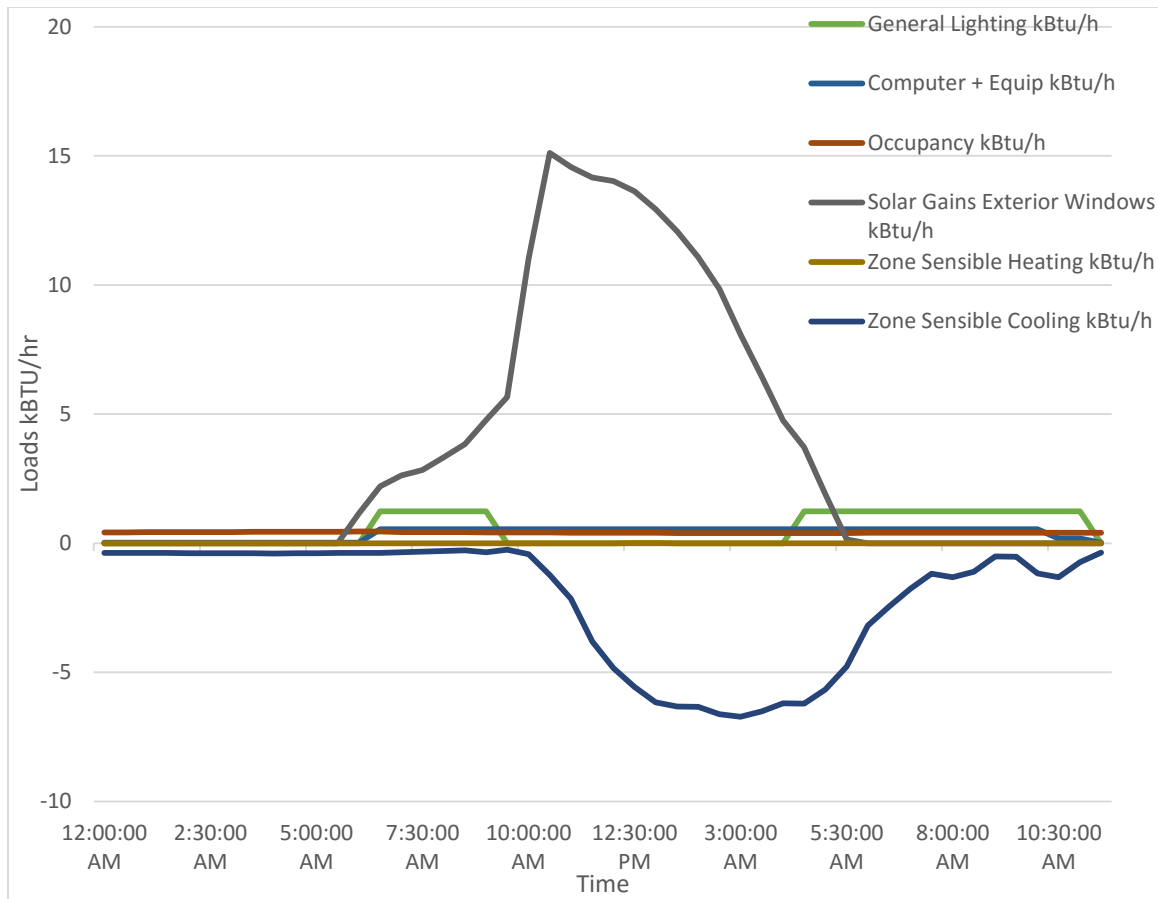


Figure 7-2. Chart of DesignBuilder calculated loads on condition space for a hypothetical October 1st for a house design with a 4-inch air gap.

The modeled peak cooling load for October 1st is approximately 8 *kBtu/hr* at 3:00 p.m.. A 1-ton air conditioning unit should be sufficient to handle the cooling load for October 1st.

The temperature within the conditioned space must be kept between 70⁰F and 75⁰F for the entire length of the competition from 27 September to 3 October 2015. The DesignBuilder model results shown in Figure 7-3 show the change in internal air temperature and relative humidity with respect to the outdoor dry-bulb temperature. The indoor air temperature

cycles with the outdoor dry-bulb temperature, but with the assistance of the HVAC system, the temperature cycles through a narrow band of temperatures.

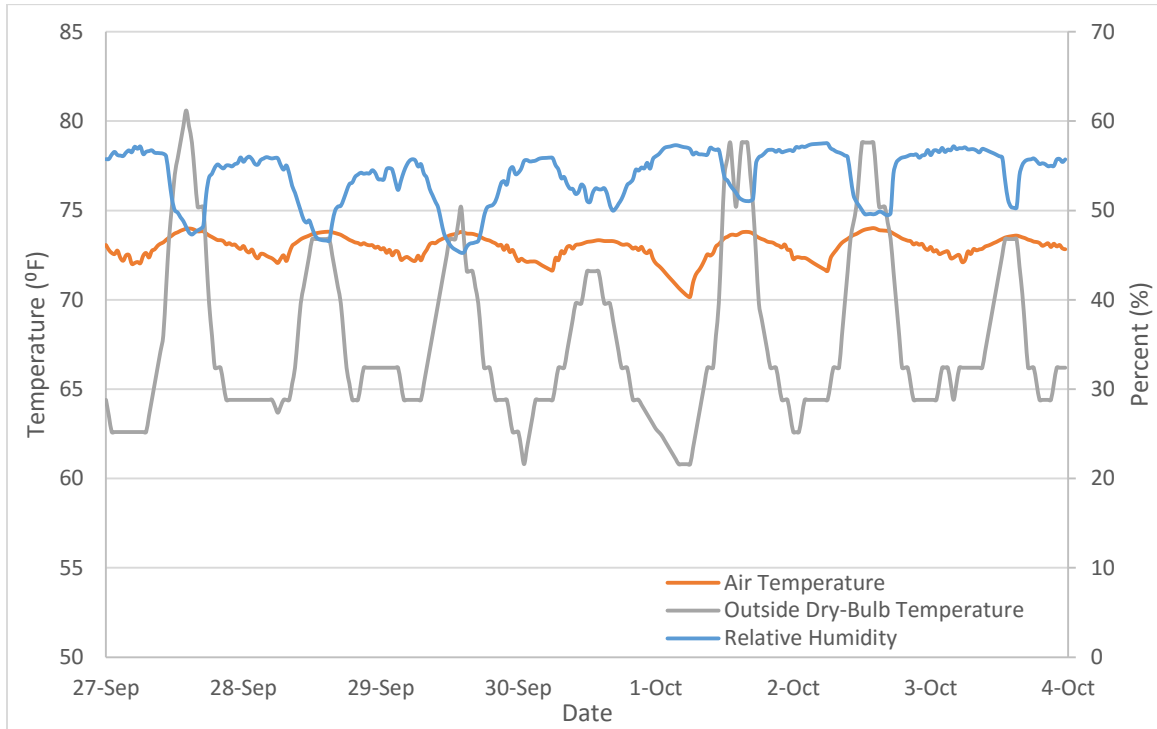


Figure 7-3. Chart of DesignBuilder modeled indoor air temperature and relative humidity with respect to outdoor dry-bulb temperature the entire competition week for the 2015 Solar Decathlon.

The same DesignBuilder model was then calculated with conventional building materials for the envelope. The results are shown in Figure 7-4.

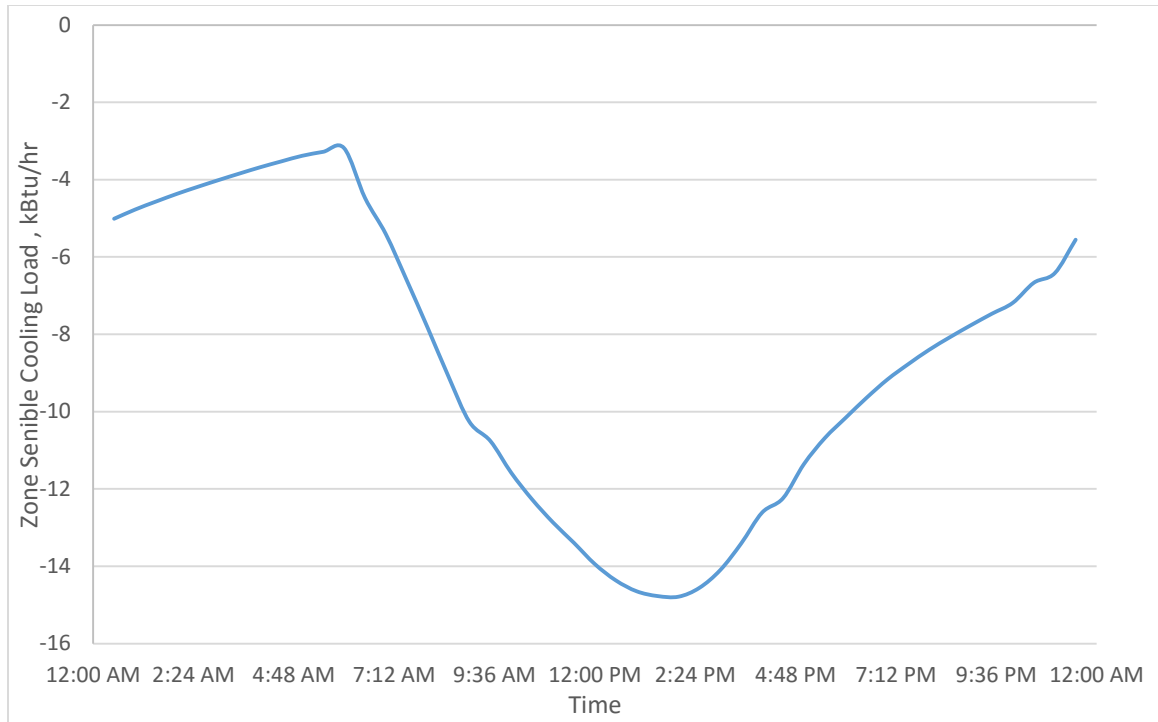


Figure 7-4. Chart of DesignBuilder calculated cooling load on condition space for a hypothetical October 1st for a house design with conventional materials.

The modeled peak cooling load for October 1st is approximately 15 *kBtu/hr* at 2:20 p.m.. Therefore with conventional practices, a 1.5 ton air conditioning system would be required to handling the cooling loads on October 1st. It is clear from this chart that the modeled design load for the Solar Decathlon competition 2015 is significantly lower for the current envelope design as opposed to conventional building materials.

VIII. HVAC SYSTEM DESIGN

With the heating/cooling loads of the house design calculated, a decision needed to be made on what type of HVAC system was going to be used in the Solar Cal Poly house. Four types of systems were investigated: hydronic system, packaged system, traditional split system, and mini-split system.

The first system analyzed was a packaged system. Packaged systems are conventionally used on large commercial and residential applications. The units are normally located on the roof or side of the building, and duct work distributes the conditioned air to the interior spaces. This system layout is the simplest of the options because the package unit contains all the required active components, so the design just requires the ducts go from the unit into the space and return back to the unit. The major issues with this design are package units tend to be larger and the model shows the system size only needs to be about 2-tons. The architecture team found the aesthetics of the package system unacceptable.

Hydronic systems are becoming increasingly popular and are very efficient, especially when combined with a planned solar hot water system. Radiant heating systems are comfortable, simple to operate, and are aesthetically pleasing. The pipe system runs under the floor, so there are no registers or cassettes, and the duct work doesn't need to be hidden. The aesthetic advantages appealed to the architects. The simple, comfortable results would be an interesting talking point for the competition. Much research has been done to model radiant systems and look at efficient design. The complexity of the design and construction process adds a significant upfront cost to radiant systems. Additionally, a separate radiant system would need to be run for cooling. The current issues with radiant cooling systems in terms of condensation and personal comfort means that a more conventional cooling

system would be used. Two separate systems for heating and cooling would add cost and further complexity. The final issue with a radiant hydronic system is that the thermal mass material used to store the energy from the hydronic system would be difficult to construct and transport.

Traditional split systems are similar to packaged systems, except the heating and cooling equipment is separated or “split”. This is a common structure for most residential buildings. Because the only equipment that is located outside is the condensing unit, the traditional split system has a much smaller aesthetic impact on the exterior of the house. The air handler and furnace are normally located in a mechanical room or unconditioned closet. Although the outdoor unit is smaller than the packaged unit’s outdoor unit, the system still requires duct work. This type of system is also quite common, so this design would not produce an unusual narrative for the solar decathlon team to discuss. In general, with the medium sized outdoor unit and the interior ductwork, the architecture team found the system unappealing as the system would require exposed ducts or a dropped ceiling.

Mini-split systems are the most recent advancement in HVAC design. They are similar to a split system in that a small condenser unit is located outside. These exterior units tend to be significantly smaller than the traditional split condensing unit. Mini-splits are actually significantly more efficient than traditional split systems. This is due to the same principle as the hydronic heating. Instead of the condensing unit refrigerant lines traveling to a cooling coil in a fan unit, the coolant lines go directly to a fan “cassette” in the space. Within the cassette, a fan circulates the air in the room over the refrigerant coil. Therefore, the mini-split system does not have the duct friction and leak losses common in forced air systems. And with well insulated refrigerant lines, more of the cooling energy reaches the

space. Additionally, many of these mini-split systems are heat pumps, which means they can be used to heat a space when the temperature is cold outside. This means that separate heating and cooling systems are not necessary. The major drawback to the mini-split system is they are not designed to be located far from their cassettes. In fact, part of their efficiency is that the refrigerant doesn't need to travel far. This shouldn't be an issue in a small 1,000 square foot house like the one for the Solar Decathlon competition. The architecture team was also very unhappy with the aesthetics of the cassettes.

It is clear that there is no perfect HVAC system for this design. The architecture team was unhappy with the aesthetics of all of the systems, except the hydronic heating. Since the hydronic system is unfeasible and would probably require one of the other listed systems for cooling it is clear that any selected system would be suboptimal for the architecture team. Of the remaining HVAC systems, the mini-split is the most efficient, and simplest system.

From the DesignBuilder model it was clear that each of the three main rooms were going to need some conditioning, but most mini-splits are designed for one zone. If multiple units were going to be needed it would be cost prohibitive for the project. A quick google search revealed that there are a few models of "Multi-Zone" mini-splits. Each outdoor condensing unit has several refrigerant ports. Each set of fluid and suction lines go to a different cassette, and the cassettes can be in different zones.

A quick product search found four companies that make multi-zone mini-splits that meet the design load criteria: Fujitsu, GREE, Mitsubishi, and Daikin. Of those companies, the Fujitsu Hybrid Halcyon Flex (Flex) had the highest efficiency (18 SEER). The condensing

unit for the Flex is shown in Figure 8-1. Although all the units are similar, the rest of this section specifies the design based on the specifications of the Flex. The specification sheet for the Flex is in Appendix A.



Figure 8-1. The 3-ton condensing unit for the Fujitsu Hybrid Halcyon Flex. (Halcyon Hybrid Flex Inverter, 2013)

Some design considerations for the layout of the Flex system came from the specification sheet.

- The liquid lines must be 1/4-inch diameter
- The suction line is 1/2-inch for the main cassette, and 3/8-inch for the rest.
- The maximum change in height of the lines is 49-ft.
- The maximum length of the lines is 164-ft.

A major design decision of the Solar Cal Poly house design is a central core such that all major HVAC and water systems are already assembled in the core. The core will be shipped to Irvine for the competition site. This set-up will simplify the assembly and disassembly of the house for the competition. On the other hand, this design decision limits the placement of the cassettes for the mini-split system.

The master bedroom is adjacent to the mechanical room. The smallest wall cassette that Fujitsu makes is 7 kBTU. It was decided to put the smallest wall cassette on the wall between the mechanical room and the master bedroom to minimize the amount of liquid and suction line required. The liquid and suction lines for the library and common area cassettes must run over the hallway, therefore, wall mounted cassettes were selected for each of these spaces as well. A 7 kBTU unit was selected for the library, and a 18 kBTU wall cassette was chosen for the common area, because that zone required the most cooling. For the entire multi-zone mini-split system, the change in height and length of the units is well within the specifications for the system. A summary of the cassette locations are shown in Figure 8-2.

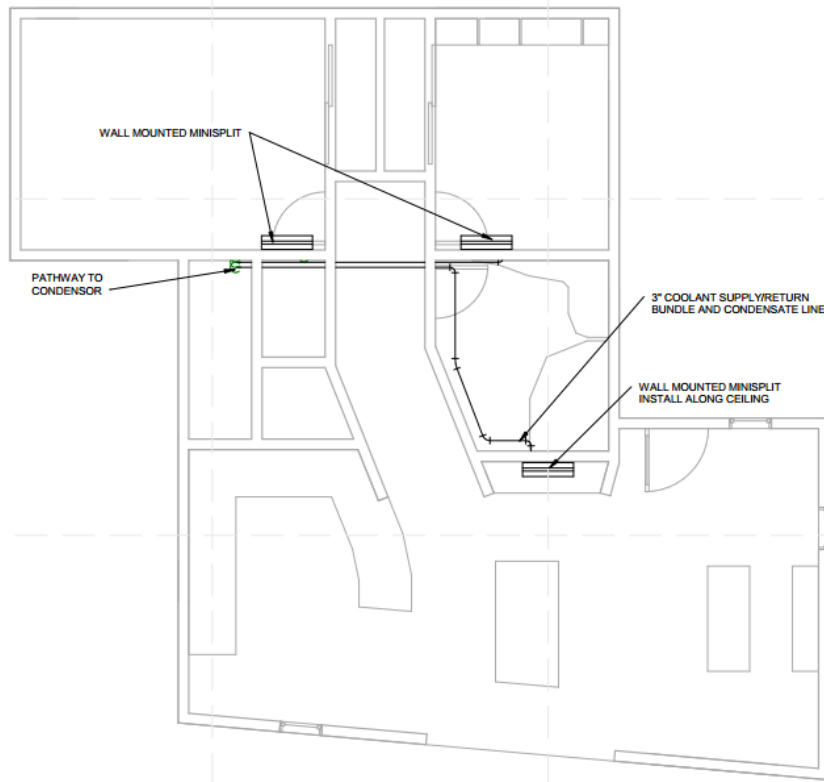


Figure 8-2. The layout of the cassette positioning in the final summer design 2014 floor plan. The coolant lines will run back to the mechanical room, and then outside to the condenser once the building is assembled on site. (Poly, 2014)

The Revit model of the cassette system is shown in Figure 8-3 with the other major use equipment, ventilation and plumbing.

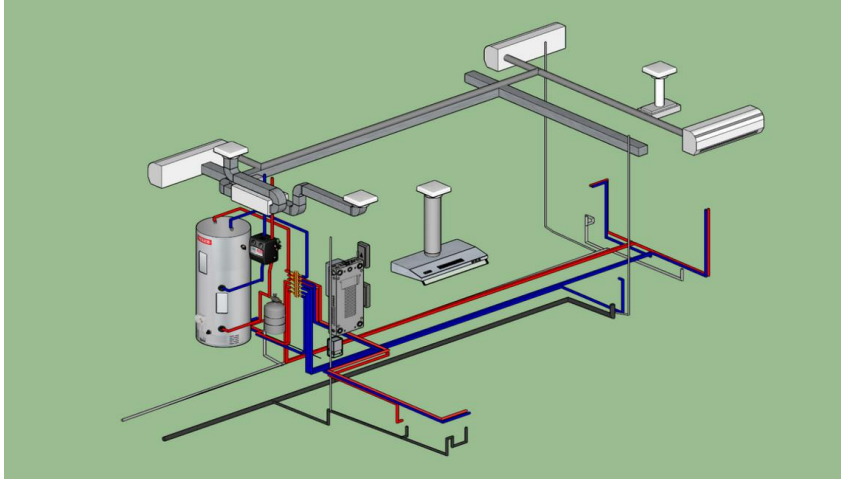


Figure 8-3. A view of the HVAC and plumbing system for the summer 2014 floor plan as it was submitted on October 2010. (Poly, 2014)

A more focused plan view of the HVAC equipment is shown in Figure 8-4. The cassettes are located within each major space. The liquid and suction coolant lines will run along the same chase as the HRV duct system. The HRV ventilation system was designed by Julien Blarel. Ms. Willis and Mr. Blarel designed the dedicated exhaust fans for the kitchen hood and bathroom together. A concern with this design is that the HRV system supplies next to the mini-split cassettes. Since the HRV system is a continuous ventilation system, it could be supplying warm air directly to the temperature sensor for the cassette. This could cause the mini-split system to run more than necessary, and potentially over-cool the space.

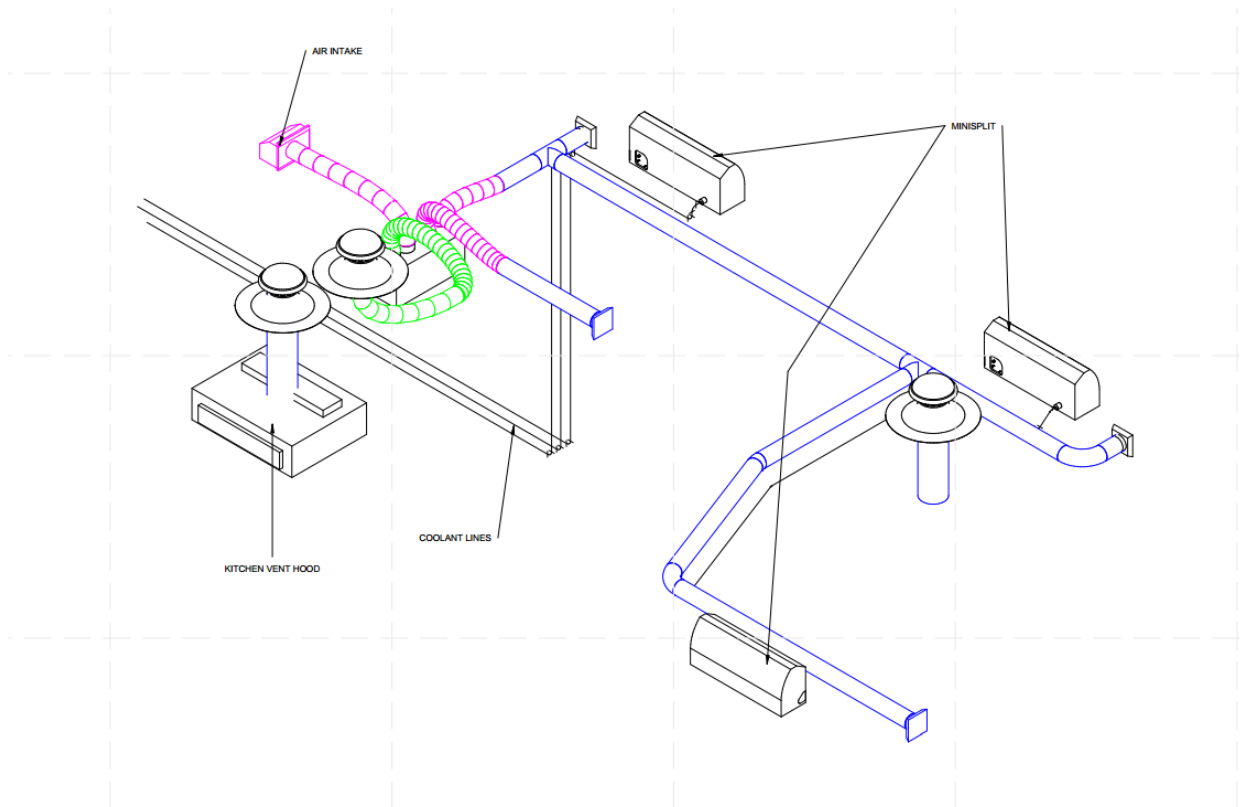


Figure 8-4. The Revit model of just the HVAC equipment submitted to the DOE for the 9 October 2014 design documentation. (Poly, 2014)

Ms. Willis proposed an intermittent ventilation system that would run at a higher speed, but only during times of the day when the outdoor air temperature was similar to the desired setpoint in the late morning and early evening. An intermittent system would not disrupt the setpoint within the space as much and therefore reduce the cooling load to offset warm air entering the space. Dr. Beller was concerned that an intermittent system would not meet the building code requirements, so the HVAC system uses a more traditional ventilation system.

IX. CONCLUSION

College competitions, like the Solar Decathlon, are an important way of educating the next generation of professional architects, engineers, and designers about green and sustainable building design. This is especially important in California, where the California Energy Commission is working toward net-zero home construction by 2020. With the increase in population and industrialization in the last hundred years, it is extremely important that humanity begin focusing on how to get the most out of our limited resources.

This project explored many different systems to keep homes comfortable with the smallest amount of resources. From ancient passive designs, like solar chimneys, to the most advanced active HVAC equipment, like mini-splits, there are plenty of ways to make a building sustainable and comfortable. It just requires having everyone who will be working on the project involved from the design phase. It is clear that passive design elements are not something that can be tacked on at the end of a design for the building to be optimized. In this project, the floor plan was developed with architects and engineers working together to optimize the building from the very beginning. This floor plan was then analyzed using the building modeling software, DesignBuilder, and the thermal loads were found. With those thermal loads, engineers and architects worked together again to find an active HVAC system that would meet the cooling and heating requirements for the house, while still being aesthetically appealing.

This documentation provides a full analysis of a passive and active HVAC design for the Solar Cal Poly 2015 Solar Decathlon final summer design. This design recommended a 2-ton mini-split heat pump. For this project, a Fujitsu Halcyon Flex was specified because it had the highest efficiency of 18 SEER. This project also lays out important information

on passive and active HVAC design and equipment and the methodology for modeling and designing HVAC systems. It is hoped that this project will not only provide useful guidance to the rest of Solar Cal Poly's mechanical engineering team as they continue to design and build the completion entry, but also future Solar Decathlon teams, Green mechanical engineers and architects, and anyone interested in working toward a world that is both sustainable and livable.

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