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A Case Study of Zero Energy Home Built for Solar Decathlon Competition 2013

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A CASE STUDY OF ZERO ENERGY HOME BUILT FOR SOLAR DECATHLON COMPETITION 2013

By

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ABSTRACT

Energy consumption in residential homes has been a subject of research related to sustainability. Reduction in the consumption of energy is a goal of sustainable construction. The Department of Energy (DOE) started a Solar Decathlon competition in 2002 in which the students from different universities around the globe build an energy efficient and affordable home suitable for their climate and location. The main goal of this competition is to select the best home that is designed and built in a sustainable way. In this study, the home designed and constructed for participation in the competition by the students at University of Nevada, Las Vegas (UNLV) has been taken into consideration. This home has been designed for the desert climate. The main objectives of this study are to describe the design and construction process of this home, the energy efficient features used in the home, the cost associated with the construction of the home, and also the energy consumed by the home. In addition to this, the energy consumption data of this home collected during the competition period in Irvine, California was compared with 30 Energy Star and 30 non-Energy Star homes in Henderson, Nevada. The results showed that the zero energy home not only produced energy sufficient to run the entire home, but also proved to be more energy efficient than the Energy Star and non-Energy Star homes built in Henderson, Nevada by consuming 2% and 6% less energy respectively.

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CHAPTER 1

INTRODUCTION

In 2012, energy consumption in the United States (U.S.) decreased by 2.4 percent, which is about 2.4 quadrillion Btu reduction in energy consumption (U.S. EIA, 2013). The United States consumed about 98 quadrillion Btu in 2011 which equals about 19% of the world's total energy consumption (U.S. EIA, 2013). Residential homes have been one of the major consumption sectors. Out of the total of 505 quadrillion Btu of energy consumed in 2008 all over the world, the residential sector consumed about 18% of the energy, making it the third highest end-use consumption sector among the four major energy end-use sectors: industrial, transportation, residential, and commercial. Residential and commercial buildings consumed about 40% of the total energy in the United States in 2012 which is about 40 quadrillion Btu. This is one of the reasons why renewable sources of energy are being emphasized to produce energy and meet the energy demand.

Approximately 19% of the electricity generated in the entire world is from renewable energy sources, which includes hydropower, biomass, biofuels, winds, geothermal, and solar, which is estimated to increase to 23% in 2035 (U.S. EIA, 2013). The United States is second in generating electricity from renewable energy after China. In 2012, 12% of electricity in the United States was generated from renewable energy sources. Out of this 12%, 56% of electricity was generated from hydropower and 1% of energy was generated from solar energy (U.S. EIA).

1.1 Solar Decathlon

1.1.1 Solar Decathlon Competition and Contests

The Solar Decathlon is a biennial competition that is organized by U.S. Department of Energy (DOE). The Solar Decathlon 2013 was held at Orange County Great Park, Irvine, California from October 3-13, 2013. Twenty different teams from universities around the globe were selected for Solar Decathlon 2013. The selected collegiate teams participating in this competition designed and built a solar-powered house that is not only energy-efficient but also architecturally appealing at the same time.

The houses in this competition are judged based on ten contests, each worth a maximum of 100 points and making a total of 1000 points. The contests have been categorized into two groups: measured contests and juried contests (Table 1). The measured contests include contests based on the task completion (cooking, washing dishes and doing laundry) and monitored performance (maintaining comfortable indoor temperature and humidity). On the other hand, the juried contests include the jurors' evaluation of the features that cannot be measured.

Table 1. Contests and Subcontests in Solar Decathlon 2013

Contest Number	**Contest Name**	**Subcontest Number**	**Subcontest Name**	**Subcontest Type**	**Total Points**
1	Architecture	-	-	Juried	100
2	Market Appeal	-	-	Juried	100
3	Engineering	-	-	Juried	100
4	Communications	-	-	Juried	100
5	Affordability	-	-	Juried	100
6	Comfort Zone	6-1	Temperature	Measured & Monitored	75
		6-2	Humidity	Measured & Monitored	25
7	Hot Water	-	-	Measured Task	100
8	Appliances	8-1	Refrigerator	Measured & Monitored	10
		8-2	Freezer	Measured & Monitored	10
		8-3	Clothes Washer	Measured Task	20
		8-4	Clothes Dryer	Measured Task	40
		8-5	Dishwasher	Measured Task	20
9	Home Entertainment	9-1	Lighting	Measured Task	40
		9-2	Cooking	Measured Task	20
		9-3	Dinner Party	Juried	10
		9-4	Home Electronics	Measured Task	25
		9-5	Movie Night	Juried	5
10	Energy Balance	-	-	Measured & Monitored	100

University of Nevada Las Vegas (UNLV) was one of the 20 teams selected from around the globe for the Solar Decathlon 2013. To participate in this competition, students from UNLV built a solar-powered home called “DesertSol.”

1.1.2 Team Las Vegas’ Rankings and Scores in the Contest

Team Las Vegas ranked second in the overall competition with a total score of 947.572 out of 1000 points. Out of the ten contests in the competition, Team Las Vegas ranked first in Market Appeal, Hot Water, and Energy Balance Contests with 94.000, 100.000, and 100.000 points respectively. In addition to this, the team ranked second in the Communications Contest with a score of 90.000 and third in the Engineering Contest. The summary of the rank and the scores obtained by team is given in Table 2.

Table 2. Rank and Scores Obtained by Team Las Vegas

Contest Number	Contest	Rank	Scores
1	Architecture	5	85.000
2	Market Appeal	1	94.000
3	Engineering	3	93.000
4	Communications	2	90.000
5	Affordability	13	95.137
6	Comfort Zone	4	98.059
7	Hot Water	1	100.000
8	Appliances	9	98.441
9	Home Entertainment	7	97.935
10	Energy Balance	1	100.000

1.2 Objectives and Scope of the Study

This case study focuses on the energy consumption of the house, DesertSol, built by the students at UNLV to participate in the Solar Decathlon Competition 2013, and compare it with the 60 typical residential homes in Henderson, Nevada.

Therefore, the main objectives of this study are:

1. Describe the materials used in the construction of DesertSol and describe its unique features
2. Estimate the cost of the home
3. Collect the simulation data of the annual energy consumption of DesertSol and energy consumption during the competition and compare these two

4. Collect the total energy consumed by the home during the competition period and compare it with the 30 Energy Star and 30 non-Energy Star homes of Henderson, Nevada area.

CHAPTER 2

LITERATURE REVIEW

During the literature review, three major areas of research regarding the energy consumption of residential buildings were reviewed. They were energy consumption trend of residential buildings in US, factors affecting energy consumption of residential buildings, and energy consumption measurement of zero-energy homes. The detailed literature review is described below.

2.1 Energy Consumption of Residential Buildings

Energy consumption for space conditioning (heating and cooling) has decreased from 58% in 1993 to 48% in 2009 because of the increased use of efficient windows, insulation, and equipment (U.S. EIA, 2013). However, due to the increased use of devices, the energy consumption by non-weather related appliances, electronics, water heating, and lighting has increased from 42% in 1993 to 52% in 2009. In 2009, appliances, electronics, lighting, and miscellaneous uses consumed about 67% of electricity by U.S. households.

In comparison to the commercial and industrial sector, the seasonal variance of electricity use by the residential sector is the highest (U.S. EIA, 2013). Residential homes mainly use electricity for the purpose of cooling the home during the summer and heating during winter. In addition to electricity, other sources like natural gas or fuel oil are also used during winter for heating. The electricity demand during summer and winter peaks can reach up to 67 billion kilowatt-hours (kWh), which is more than double that of the commercial sector and more than three times that of the industrial sector’s summer peak.

The newer homes built during 2000 to 2009 consume only 2% more energy than homes built before 2000, even if the newer homes are 30% larger in size than the older ones (U.S. EIA, 2013). The newer homes consumed 21% less energy than the old ones for space heating, which is due to the use of efficient equipment and an improved envelope with the homes. On the other hand, 3%, 56% and 18% more energy were consumed by new homes for water heating; air conditioning; and appliances, electronics, and lighting, respectively, as compared to homes built before 2000.

As compared to past energy consumption, residential energy consumption from electricity has increased. This is in contrast to natural gas, which has been nearly constant for decades, and other fuels that have decreased (U.S. EIA, 2013). This increase is due to the increase in the number of devices per household. In addition to this, the percentage of central air-conditioning used in the homes has increased from 45% in 1993 to 60% in 2009.

In 2012, an average of $1,945 was spent by households on heating, cooling, appliances, electronics and lighting (U.S. EIA, 2013). This accounts to 2.7% of the income of the household, which is the lowest in the past 10 years. The expenses of energy consumed by household utilities, such as water and telephone services as well as transportation, were not included in this average. In addition to this, the expenses for home energy by U.S. households decreased by $12 billion in 2012 as compared to 2011.

2.2 Research Related to Energy Consumption of Residential Buildings

Shrestha and Kulkarni (2010) conducted a study to identify the factors affecting the energy consumption of residential buildings by collecting data from 30 homes built in 2001, 2005, and 2008 in Henderson, Nevada. The results showed that the energy consumption (electricity and natural gas) in the residential home increased with the increase in floor area of the homes. The homes built in 2008 consumed less electricity than the homes built in 2001 and 2005. The homes with double pane low-e windows consumed the least energy compared to the homes with single pane and double pane windows. Another finding was that the older the age of the air conditioner and the more frequent use of the air conditioner, the higher the electricity consumption was. Also, the lower the thermostat temperature was set during summer, the higher the electricity consumption was. The electricity consumption increased with the increase in the age of the clothes washer and increased use of the washer. The authors observed that the room temperature setting during winter was correlated to the mean annual natural gas consumption per area. The annual natural gas consumption per area increased with the increase in the use of the clothes dryer.

Kosny et al. (2001) performed simulations and compared the heating and cooling energies consumed by three residential houses for ten different U.S. climates. Two models of all three houses were created, one with massive walls and the other with lightweight wood-frame exterior walls. The R-value required for the houses with lightweight wood-framed walls to consume the same energy as houses with massive walls was determined from the results. Also, out of ten different U.S. climates, thermal mass walls were observed to be more energy efficient in Phoenix, Arizona, and Bakersfield, California. Simulation models of houses with massive walls and lightweight wood-frame walls for two locations, one in Minneapolis, Minnesota (cold climate) and the other in Bakersfield, California (hot climate), were created and the results were compared to find the energy savings in these two locations. In the case of Minneapolis, where more heating was required, it was observed that a massive wall system could save as much as 8% of energy compared to a conventional wood-framed wall. On the other hand, in the case of Bakersfield, California, where more cooling was required, it was observed that a massive wall system could save as much as 12% of energy compared to a conventional wood-framed wall. Moreover, the authors performed a simulation to study the energy saved by insulating concrete form (ICF) walls as compared to a conventional wood-framed wall. Results showed that an ICF wall saved about 6% to 8% more energy.

Wilkinson and Boehm (2005) studied the energy efficient features that could be applied in a residential home in Southern Nevada area to make the home a net-zero energy home. For this, the authors simulated a model called the Reference Case and used the results to create a Low Energy Case. From this simulation, the total energy consumption for the base case was observed to be 18.56 kWh/ft^2. Of this total energy, the maximum energy 6.24 kWh/ft^2 was consumed for heating load and the minimum energy 0.88 kWh/ft^2 was consumed by lighting. The finding of the study showed that the double low-e glazing's energy consumption was almost as same as that of triple glass window with 3.91% energy savings. Also, in case of the four different cases simulated for window framing, vinyl window frame was observed to be more energy efficient saving 7.33% of energy on a yearly basis. In addition to this, it was observed that the sloped shading was more effective towards energy savings than the horizontal shading. In case of slab insulation, the authors found that fully insulated (R-10) slab was most energy efficient by saving 12.31% energy in a year. It was also observed that this type of slab was more than 10 times efficient towards saving energy in heating than in cooling energy consumption. Moreover, out of the three cases of exterior wall that the authors studied, Insulated Concrete Form (ICF) walls proved to be energy efficient, saving 6.40% more energy than the conventional walls. Also, when the R-value was increased from R-30 to R-60 the annual energy savings increased by 5.65%. Instead of real on-site blower door test, the authors' simulation showed 14.67% reduction in the annual energy consumption because of tight envelope. In contrast to the conventional cooling unit with Energy Efficiency Ratio (EER) 9 used in the Base Case, the Freus unit with EER-16 was used in the simulation which saved nearly 50% of the cooling energy and 13.14% of the overall energy consumption. Locating the ducts from unconditioned space to the conditioned space, 13.78% annual energy saving was observed. In addition to this, it was also found from the simulation that there was 25.35% and 16.85% reduction in the heating and cooling energy consumption respectively. Increasing the gas furnace efficiency by 14%, the authors observed 5.11% energy saving in a year. It was also observed that the heating energy consumption decreased by 15.50%. Instead of using incandescent lights as in case of Base Case, simulation was done using fluorescent lights in simulation which showed 3.30% of annual energy saving. The authors used a "batch" type solar domestic water heater combined with on-demand tankless water heater, which was roughly assumed to reduce the water heating energy consumption by 80%. From the electricity consumption observed in the house, the authors determined the size of photovoltaic system to be 4.8kW capable of producing 8,100 kWh. Replacing the conventional features in the Base Case by the energy saving features found from the simulation, the authors found almost 60% reduction in the annual energy consumption with more than 50% reduction in just the electrical energy. In addition to this, the annual energy cost was also reduced by almost 60%. Envelope, energy efficient appliances, and solar control were emphasized during the study, which resulted in the saving of annual electrical energy by 105%. The heating and cooling energy consumptions were also reduced by 96% and 72% respectively.

Wang, Gwilliam, and Jones (2009) conducted a study to find the probable solutions to build a zero energy home in United Kingdom (UK). For this purpose, they performed a total of 64 different cases of simulations of the house and the results were used for the design of the building envelope, building system, and renewable energy systems. From the collected data, the authors found that south-facing homes with window-to-wall ratios (WWR) of 0.4 for south-facing rooms and 0.1 or less for other sides facing rooms were observed to be the most energy-efficient passive design for the house. This decreased the heating energy by 26.5%, whereas, slightly increased the annual cooling energy. In addition to this, with improvement in the U value of the glazing of the window and roof, the annual heating demand was reduced by a total of 252.8 kWh and the annual cooling demand was reduced by a total of 41.6 kWh. Even though the efficiency of the flat-plate solar collector was observed to be 35% and solar factional energy saving to be 78.5%, almost 22% of the additional energy was required for the domestic hot water. Installing the underfloor heating system could reduce the setting temperature by 2^{o}C and the annual energy consumption was reduced by 861.1 kWh. The simulation results also showed that lighting and appliance, auxiliary heating in solar domestic hot water (SDHW), and floor heating consumed 4672.0 kWh, 401.7 kWh, and 935.2 kWh of energy respectively. On the other hand, the annual power generated from both PV and wind turbine was observed to be 7305.9 kWh out of which 9% was generated from PV and 91% from wind turbine. This also showed that, 1297.0 kWh of extra energy was generated.

2.3 Research Related to Zero Energy Homes

A Zero Energy Buildings (ZEB) design involves two approaches: reducing the energy need in the building and using renewable energy for the required energy needs (Li, Yang, & Lam, 2013). Building envelopes, internal conditions, and Heating, Ventilation, and Air Conditioning (HVAC) and lighting highly influence the energy consumption in a building. Over-insulation can increase the energy consumption beyond certain point and thus should be avoided. The rate of heat loss from the insulated wall during the cooling mode is reduced if a building is over-insulated, which increases the energy consumption. Also, efficient design of daylighting and lighting could also save significant amounts of energy.

The authors studied 20 homes; 10 Net Zero Energy Homes (NZEH), 9 Near Net Zero Energy Homes (NNZEH), and 1 home that was only Energy Star certified in New England, for a year to see if these homes could achieve net zero energy or not (Thomas & Duffy, 2013). Moreover, they also compared the actual data with the modeled data and also studied the common factors of the home that affect the energy consumption. From this study, it was found that six out of ten NZEH were able to achieve net zero. It was also observed that all homes had some common design aspects such as, high levels of insulation (exceeding the code requirements) and better quality of sealing to avoid leakage, energy efficient appliances, Compact Fluorescent Light (CFL) /Light-Emitting Diode (LED) lighting, and high-quality windows. The average energy consumed by the NZEHs and NNZEHs was almost 90% less than the Energy Star home. The NZEHs consumed 14% less energy than predicted whereas the NNZEHs consumed 38% more energy than it was predicted. Moreover, the actual electrical energy generated by the PV panels in the homes was within a range of ± 10% for the majority of the homes. The authors concluded that behavior of the occupant was the major reason for the variation in this predicted and real energy consumption. In addition to this, other reasons were hotter temperatures than average, mechanical problems, and simplifications adopted during the modeling.

In the first year, it was observed that a Zero-Energy Home (ZEH) used significantly less electric energy than the baseline home (Rosta, Hurt, Boehm, & Hale, 2008). It was also observed that the ZEH only consumed electric energy during the hot season, for four months from June through September, when a cool temperature inside the home was required. However, the energy produced from the solar panels in the ZEH was sufficient for the home itself for the remaining months. Even though the authors encountered a plumbing problem in the heating system of the home during the first year, the ZEH still used 50% less energy than the baseline home. The overall energy saved by the ZEH as compared to the baseline home was more than 80%. In addition to this, the authors also calculated the efficiency of the PV panel to measure its performance. The authors observed that during the same four months, the efficiency of the PV panels was less when both the PV cell temperature and the surrounding temperature were high. Considering all the energy consumed by the ZEH as well as the extra energy consumed due to the plumbing fixture problem, the ZEH still proved to be more energy efficient than the baseline home and produced 1700 kWh more energy.

Madeja and Moujaes (2008) studied differences in energy consumption in identical real homes: a Zero Energy Home (ZEH) with energy efficient features and a traditionally built baseline home. The authors then compared the obtained data with their simulation data. They observed that the use of thermal mass in the ZEH resulted in a maximum energy consumption of only 25% of the baseline home during cooling of the ZEH. However, from the simulation results of the baseline home, the authors observed that the simulation model overestimated the thermal mass of the structure than in the real home. Thus, the simulation model estimated 2.25% more energy consumption for cooling and 6% less energy for heating than in the actual home. Furthermore, the simulation results of the ZEH for cooling showed 11% more energy consumption than in the actual home. In an overall analysis, the authors found that the ZEH saved 76% energy than the baseline home, which was 1% more than the predicted simulated results.

Zhu, Hurt, Correia, and Boehm (2009) studied and collected data: one from a traditional house (baseline home) and the other from zero energy house (ZEH), both built in Las Vegas, Nevada. The wall thickness and overall R- value was 62.5 mm and 2.15 ($m^2\,{}^oC$)/W, respectively, for the baseline home; and 204 mm and 2.06 ($m^2\,{}^oC$)/W, respectively, for the ZEH. These were the main components for comparison in energy consumption. The results showed that the internal wall temperature varied significantly according to the external wall temperature in case of baseline home. In the case of the ZEH, the temperature remained more constant in both heating and cooling seasons because of its heat storing ability. Furthermore, the authors stated that overall energy consumption for the mass wall house was less than the baseline house by 14 kWh. They concluded that the mass wall was able to stabilize the indoor temperature better than the conventional walls as it can store heat at day time and release it at night but for deserts where more sunlight is available, more heat will be stored and released inside the house leading in the increment of the cooling energy consumption. It was also observed that the mass walls reduced the energy consumption and was advantageous during heating season; however, the energy consumption was comparatively higher than the baseline house during cooling season.

Energy consumption of homes used for Solar Decathlon was greatly influenced by the water heating and Heating, Ventilation and Air Conditioning (HVAC) systems used (Wallpe, Hutzel, Lasker, & Cory, 2012). The author describes that out of 7 houses that reached net zero, 5 used heat pump water heaters for drawing hot water in case of no adequate sunshine. This proved to be beneficial for the teams during the cloudy weather days of competition. The author further stated that even though the solar thermal systems may have had a high initial cost, almost 5 times more than the heat pump heaters, they could be more economical in the future. The author explained that the angle of tilt of the photovoltaic array also had an impact on one of the teams. The team used one of the best photovoltaic systems but still the performance was not that good because the module was placed horizontally. In addition, due to high humidity during competition period, 13 houses could not maintain both temperature and humidity at the same time due to use of ductless mini-split HVAC system which required a separate dehumidification system. Performance on dehumidification of two teams whose scores were high in comfort zone competition was outstanding however their cost was over $20,000. Unlike other teams, only the Purdue IN home used a traditional forced-air HVAC system which not only maintained the humidity but also the temperature. The paper states that, this system may not be the best one in comparison to the ductless mini splits but are energy efficient, available and affordable today.

CHAPTER 3

MATERIALS AND METHODOLOGY

It is important to understand the construction features of DesertSol including the energy efficient appliances and energy-saving designs used in the house. So, in the first part of this Chapter the design and construction features of the home has been described. In the second part of this Chapter, the methodology applied in this study has been described.

3.1 Solar Decathlon Home – Design and Construction

The home designed and constructed by UNLV for Solar Decathlon is a single story, 802 square foot, suitable for a vacation home (Figure 1). The home is built in two modules connected by a bridge. The two modules can be easily separated, transported, and assembled. The bridge separates the two modules, Module A (west side) and Module B (east side), basically into the private and public space inside the home. The bedroom, laundry, bathroom and also the mechanical room is in Module A, whereas the reconfigurable living space is in Module B, which can be used for cooking, dining and entertaining. The built-in cabinets in this module provide ample storage.

Because the water is scarce in Las Vegas area, to maximize the use of storm water, it is designed to collect rainwater. The water feature between the two modules on the north side of the bridge provides opportunity for evaporative cooling, rain water collection, and gray water filtration. Some of the pictures included here are not taken by the authors but are taken by the team mates of Team Las Vegas, UNLV.

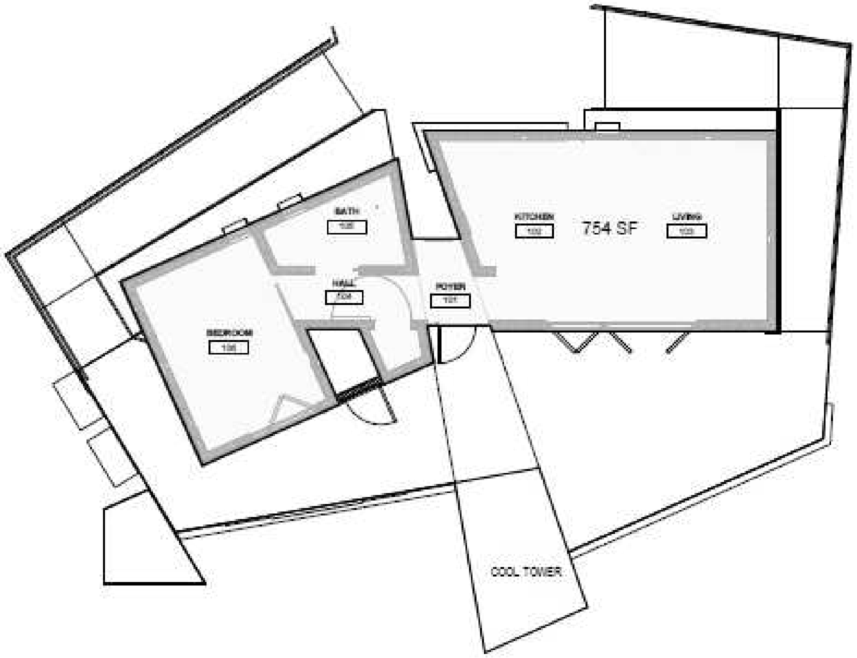

Figure 1. Finished Square Footage Plan

Figure 2. South Face of DesertSol

Figure 3. North Face of DesertSol

3.1.1 Structural System

The two modules of DesertSol were permanently built on a steel chassis. The chassis had removable axles and hitch which were used during the transportation of the home. In addition to this, the chassis also acts as a structural system for the floor. Unlike the typical wall framing of 2x4's placed at 16-inches on center, the framing of DesertSol was based on 2x6's placed at 24-inches on center. This framing system allows use of fewer studs and also increases the thickness of the wall which can be used for providing more insulation to the home. One of the other challenges for the structural design was the long clerestory window on the north side of Module B. The length of the window interrupts the framing system. For this, the steel windows were designed to transfer the structural load from the studs above the window to the studs below the window.

3.1.2 Shade Screen System

The digitally-fabricated metal screens outside the bedroom in the patio space allow the sunlight to enter the home as well as shade the home. Both fixed and operable screen systems were used. From the architectural point of view, small holes were cut into the steel screen panels forming an image of a mesquite tree that represents the Mojave Desert. On the other hand, from the engineering point of view, in summer, the screens act as an enclosure for the home, providing shading for the patio space and also to the home. During the day time it provides shading, whereas at the night time it allows the heat to escape. In addition to this, during winter, the operable screens when opened allow the sun to penetrate into the building and heat it that ultimately reduces the energy consumption of the home.

3.1.3 Wall Construction (Exterior and Interior Walls)

One-inch closed-cell spray foam insulation with a thermal resistance of R 6.7 on the exterior side and 4.5-inch open cell spray foam insulation with a thermal resistance of R 16.65 in the interior side was sprayed between the 2x6 framing in the exterior walls. The R-value is the measure of the thermal resistance of the insulation material used in the building. Higher R-value indicates greater resistance to the heat flow. The spray foam was covered with 3/8-inch-thick plywood sheathing on the exterior side of the home. The entire home was wrapped by Tyvek Stucco Wrap for an air and moisture protection barrier on the exterior. One-inch foil-faced rigid foam insulation was placed on top of this home-wrap in between the furring strips, which was held in place by 7/8-inch hat channels at 16-inches on center. This hat channel also provides proper air flow on the wall surface. Weathered wood rainscreen was used as a finishing layer on the exterior. This rainscreen shaded the building from the sun during the day time and was also provided with ventilation in order to allow the heat to escape during the night time. Figure 4 shows the section of the exterior wall. On the other hand 5/8-inch type ‘X’ gypsum board with a level 5 painted finish was installed on the interior. The gypsum board was covered with finished plywood on the interior. The overall R-value of the exterior wall after spraying was 23.4. The interior wall was also based on the 2x6 framing with spray foam insulation in it. The insulation was covered with 5/8-inch thick type ‘X’ gypsum board painted on either side. In the case of the interior walls, the gypsum board was covered on both sides with the finish material as designed.

Figure 4. Exterior Wall Sections

3.1.4 Roofing System

The roof of the home was insulated with 1-inch closed-cell spray foam insulation with a thermal resistance of R 6.7 on the exterior side and 11-inch open-cell spray foam insulation with a thermal resistance of R 40.7 on the interior side. The spray foam insulation was sandwiched between the 3/8-inch plywood on the exterior and 5/8-inch Type ‘X’ gypsum board with a level 1 primed finish on the interior. A water proofing membrane covered the plywood on the exterior. A one-inch rigid insulation was placed on top of the water proofing membrane on which the standing seam (metal finished roof) rests. The overall R-value of the ceiling area after spraying the insulation was R 47.4.

3.1.5 Flooring System

The finished floor was the top most interior surface of the several layers of the floor (Figure 5). 1/8-inch plywood sheathing underneath the finished floor covered the 5/8-inch sub-floor. The 5/8-inch subfloor rests on the 1 and 1/8-inch structural sub floor which ultimately is laid on the steel chassis. The hollow space made by the C-channel of the steel chassis was filled with insulation: 1-inch of closed-cell spray-foam insulation with a thermal resistance of R 6.7 covered by 9-inches of open-cell spray-foam insulation with a thermal resistance of R 33.3 below the chassis. The total R-value of this insulation was found to be R 40. No-burn-plus XD ignition barrier spray was applied at 3 mils over the open cell spray foam insulation for fire resistance. Underneath, the entire chassis was covered with bottom board to provide moisture protection.

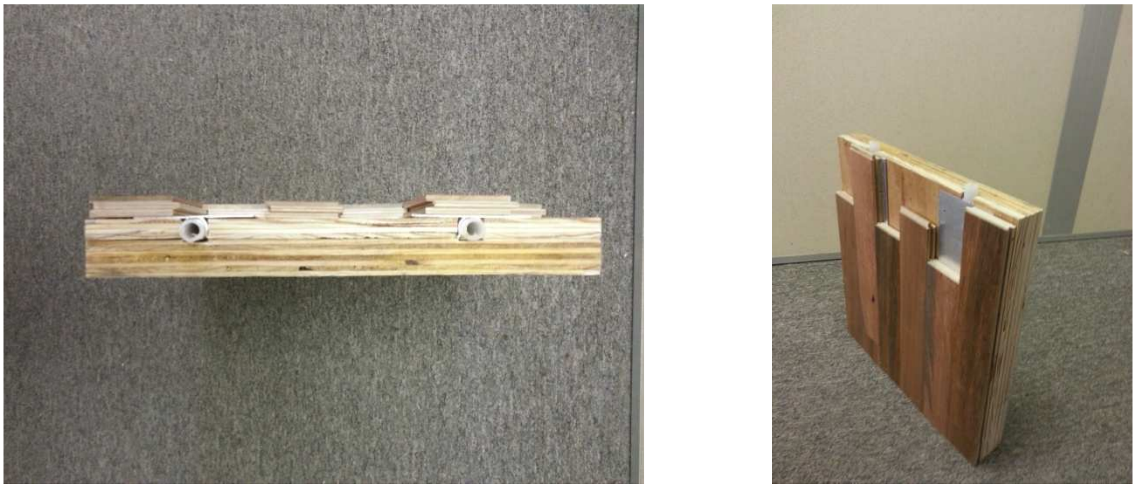

Figure 5. Floor Sections

3.1.6 Doors, Windows and Glazing

All the operable windows in the home provided to create cross ventilation were manufactured by Nanawall. In addition to this, Nanawall also manufactured the exterior doors of the bedroom, living room, and foyer. The Nanawall product is qualified as Energy Star material (Nanawall, 2013). As per the 2010 Energy Star qualification, the product needs to have a U-factor that should be less than or equal to 0.32 and the Solar Heat Gain Coefficient (SHGC) should be less than or equal to 0.30 for doors in all climate zones. The windows have an approximate total opening area of 62 sqft. The glazing used in these doors and windows was double-glazed low E insulated tempered argon filled with warm edge spacer and the frames were clear anodized aluminum. The Nanawall doors of the living room, bedroom, and foyer were mounted on the floor with stainless steel rollers. For the doors, the center of glass U-factor is 0.26 with a glass thickness of 15/16-inch. In addition to this, the SHGC for the doors is 0.23. The doors and windows sills are also sealed with the Tyvek Stucco Wrap for moisture protection and air infiltration. To protect against the water penetration, the flashing tape was used at the windowsills to adhere the Tyvek. In addition to this, low expanding insulation foam was also used in the small openings and holes in the jambs of the doors and windows.

To control the amount of daylight entering the home, most of the glazing is provided on the South and North sides of the home and minimum glazing is provided on the East and West sides. The total area of glazing provided in the clerestory window on the North and West side of Module B is approximately 61sqft. Clerestory windows were placed high inside the home so as to provide enough lighting in all the corners of the home. This helps in the reduction of the energy consumption by reducing the use of the electric lights.

3.1.7 Air Conditioning System

A ductless minisplit heating system was installed for the purpose of heating or cooling the home. Two Mitsubishi MSZ-FE09NA indoor units and two Mitsubishi MUZ-FE09NA outdoor units were installed separately in the two modules. The first indoor unit was installed on the west wall at the north-west corner of Module A and the second unit was installed on the east wall at the north-east corner of Module B. The outdoor units were installed on ground-mounted equipment pads, away from the decks and the access walkways, and were protected by well ventilated protective barriers. Both indoor and outdoor units have a rated capacity for cooling and heating of 9,000 Btu/h (2.64 kW) and 10,900 Btu/h (3.2 kW) respectively (Mitsubishi, 2013). This system uses an environmentally-friendly R410A refrigerant that reduces the impact on the ozone layer. Both the indoor unit and the outdoor unit used in this home have a SEER value of 26.

The main advantage of having two separate units is that, it allows the unit to be shut off when the space is unoccupied or simply when the space does not require air conditioning, therefore using energy only when required. In addition to this, in case of failure of one unit, there will be a second unit to provide backup for maintaining comfort until the failed unit is repaired. The other main advantage of this ductless system is that it reduces the chances of leakage of the conditioned air into the unconditioned space. The conditioned air is directly used in the space where it is required without having any chance of leakage.

3.1.8 Ventilation System

A passive system was also designed for the purpose of cross ventilation. The clerestory window on the top of the north wall of Module B and the south wall provides cross ventilation to the home by allowing the hot air to flow out from the interior. In case of the active system, a Panasonic FV04VE1 Energy Recovery Ventilator (ERV) was installed on the ceiling of the hallway to exchange the fresh air from the outdoor to the interior of the home and was connected to the home automation system for control. The ERV uses the temperature and humidity of the exhausting air and transfers the heat as well as moisture to the incoming air to match the temperature and humidity of the interior of the home. However, the incoming air and exhausting air do not mix. One of the two 4-inch ducts that supply the fresh outdoor air into the home, come out from the east wall at the north-east side of Module A. The other 4-inch duct, that exhausts the stale indoor air to outside, comes out from the east wall right above the foyer ceiling. The minimum distance of 10 feet between these two ducts, recommended by the manufacturer, was also maintained. In addition to maintain the indoor air quality, the ERV also balances the air pressure within the home by replacing the exhaust air with fresh outdoor air (Panasonic, 2013). The ERV helps reduce the heating and cooling loads by helping to maintain the indoor air quality. Using an ERV also reduces the total energy consumed by the home, because it reduces the total load in the air-conditioning system.

Exhaust fans were installed in the bathroom and in the kitchen. The Broan QTRE100S exhaust fan installed in the bathroom provides ventilation as well as exhausts the humid indoor air from the bathroom to the outside. The Energy Star-rated humidity-sensing fan exhausts the air through a 4-inch duct to the East side of Module A. The kitchen area is one of the other areas where heat, odors, and humidity are generated while cooking. In order to remove this, an exhaust fan in the kitchen area was also installed.

3.1.9 Photovoltaic (PV) Panels

The number and the capacity of the photovoltaic panels were determined from the simulation. From the simulation it was obtained that 30 solar panels with production capacity of 6.75 kW power would be required for the home to produce as much energy as it consumes. Therefore, a total of 30 SunPower SPR-225-BLK-U solar panels were installed on the roof at an angle of 11^{o}. Out of the 30 panels, 21 panels were installed on Module B, whereas, 9 panels were installed on Module A. The PV array on Module B extends over the patio space to create an overhang. This allowed more space for the PV panels for more electricity generation as well as provided shade to the home which reduced the cooling loads. Micro-inverters were used with each PV panel instead of a central inverter for all the PV panels. This allows the PV panels to work efficiently even if a part of the PV panels are shaded or not working.

3.1.10 Solar Thermal Collector System & Hot Water System

A solar thermal collector system was also installed for the purpose of water heating. The solar thermal collector system was installed at the Southwest side of the home outside the bedroom. The system was inclined at an angle of 51^{o}, which was determined during the design phase to maximize the solar radiation incident on the system. The hot water from the evacuated tube collectors (ETC) is pumped to the lower coil in the hot water storage tank and back out of the tank. The hot water itself is not dumped into the hot water storage tank instead it heats the water in the tank by transferring the heat through the coil. A Steibel Eltron tankless hot water heater model

DHC-E12 was used as a backup for the hot water purpose when the solar thermal collectors are unable to maintain the required temperature in the tank. The hot water in the tank is used for domestic hot water purposes. Besides being used for domestic purposes, the hot water in the storage tank also heats the upper heat exchanging coil which is used for the radiant floor heating purposes.

3.1.11 Radiant Floor Heating System

The radiant floor heating system is the primary heating system for the home and has been designed to use the solar thermal energy collected through the evacuated tubes to heat the home. The system is designed such that, when there is sufficient heat energy in the solar thermal storage tank, the radiant floor heating first operates to heat the interior of the home. And when there is insufficient heat in the solar thermal storage tank due to cloudy weather or cold nights, the control system allows the minisplit units to operate in the heating mode. The minisplit heat pumps provide redundancy in the system if there is any problem in the solar thermal system or during any long periods of cloudy days.

The radiant floor heating has been used to heat a total area of 546 sqft that includes 350 sqft of living area, 154 sqft of bedroom area, and 42 sqft of bathroom area. A total of four loops run all over the home except for the mechanical room. Two loops in Module B cover the whole living area whereas in Module A, one loop covers the bedroom area and the other loop covers the bathroom area.

Routes for the conduits of radiant floor heating were designed as required for the heating purpose. Uponor 1/2-inch hePEX tubing was snapped into the channel of the 4-inch wide Uponor Joist Trak Heat-Transfer Panel along the prefixed routes. The tubing was placed at a distance of 8-inches on-center and was placed on the routes as per the design drawings. The ideally stratified hot water storage tank installed in the mechanical room of the home is used to heat the water running through the tubes for the purpose of radiant floor heating. However, the water in the tank itself is not circulated through the conduit of the radiant floor heating. The temperature of the hot water going into the loop is maintained at 90^{o} F. The cold water returning from the other end of the loop is connected to the Uponor #A5401112 – 1-inch three-way tempering valve set at 90^{o}F, in addition to its path back to the hot water tank. Thus, if the temperature of the water in the loop exceeds 90^{o} F before entering into the home, the valve opens to allow the returning cold water to mix with the hot water so that the temperature remains constant.

The only electricity-consuming component in this radiant floor heating system is the pump that circulates the hot water from the tank to the four loops in the home. The Taco 110 Series-Model 112 pump with 3/4-inch flanges and a capacity 1 gpm at the rate of 1 ft H2O was used. The system collects solar energy, which is used for the heating purpose of the whole home, which makes the whole system more energy efficient than other heating mechanisms by trying to offset all the energy used.

3.1.12 Appliances

The type of the appliances being used in a home makes a significant difference in the energy consumed by the home. All appliances used in this home were manufactured by Bosch. The Bosch built-in refrigerator model COMBI 30 IN B30BB830SS used in the home is an Energy Star-qualified product (Bosch, 2013). The estimated yearly electricity use by this product is claimed to be around 388 kWh. Moreover, the estimated yearly operating cost of this product, as claimed by the manufacturer, is $41. The cost range of similar models varies from $48 to $58. However, this was the electricity consumption claimed by the manufacturer, which also depends on the utility rates and the expected use by the users or the consumers. The features of the product such as vacation mode, economy mode makes it more energy efficient. In addition to this, another feature like the alarm indicating if the door is open also helps in less energy consumption. Moreover, the Light-Emitting Diode (LED) lighting used in the refrigerator also contributes to reduce the energy bills more than a typical incandescent bulb. The recommended temperature setting for the refrigerator is 37^{o} F for the refrigerator and 0^{o} F for the freezer.

The Bosch 18-inch Special Application Panel Ready Model SPV5ES53UC Dishwasher is an Energy Star-qualified product. The company claims that the product exceeds Energy Star requirements for water by 68%. Also, EcoSense™ reduces the energy usage by up to 20%. When small, lightly-soiled loads are to be washed or when the dishwasher is only half filled or less filled than its capacity, then the users can choose The Half Load Option which not only reduces the water consumption but also the energy consumption. The estimated energy consumption by this product is 259 kWh/yr. The estimated yearly operating cost of the dishwasher is $27, when used with an electric water heater and $22 when used with a natural gas water heater. The yearly operating cost of other similar models range from $20 to $50.

The washing machine is a Bosch Model WAS20160UC which is also an Energy Star-qualified product. In addition to this, the product exceeds Energy Star requirements by up to 63%. The internal water heater in the washer heats the water quickly and efficiently. The capacity of the washing machine is 2.2 cft. The manufacturer’s estimated energy consumption based on four wash loads a week is 140 kWh/yr. In addition to this, the water consumption is 3904 gal/yr. The estimated yearly operating cost, when used with an electric water heater, is $15. This lies in the lower cost range as compared to that of similar models that varies from $10 to $71. However, when used with a natural gas water heater, the estimated yearly operating cost is $12. The estimated operating cost of the Bosch products is based on 2007 national average electricity cost of 10.65 cents per kWh and a natural gas cost of $1.218 per therm.

Although the Bosch Induction Cooktop Model NIT 3065UC used in the home is not an Energy Star product, the manufacturer of this product has highlighted its other features that can contribute towards saving energy as well as time for the user. The SpeedBoost^{TM} feature of this product is capable of heating water twice as fast as a conventional ceramic cooktop which saves time as well as energy. The other feature, PotSense^{TM}, with this product automatically adjusts the cooking element to the size of the bottom of the pot or the utensils being used which reduces the energy being consumed making it more energy-efficient and also reduces the temperature of the kitchen. The other features like the Keep Warm Function, Anti-Overheat System, and 2-Level Heat Indicator also contribute in reducing the energy consumption by maintaining the temperature. The sizes of the 4 cooktop burners vary from 6 inch to 11 inch with the power of the heating elements ranging from a minimum of 1.4 kW to a maximum of 3.6 kW.

Two Haiku Bigassfans (ceiling fan) used in the bedroom and the living room is also an Energy Star product. According to the company’s website, this fan can be 80% more energy efficient than the conventional fans. The company claims that the fan uses only 2 to 30 W of electricity and exceeds the Energy Star requirement for CFM/W by

450% to 750% which is less than 50% of the energy consumed by an average Energy Star residential fan. In addition to this, the company also claims that the annual estimated energy consumption by this product is 50 kWh which makes the yearly operating cost of around $5.

3.2 Methodology

For the purpose of energy consumption study, three types of data were collected; the first is the energy consumption data of DesertSol obtained from simulation, the second is the energy consumption data of DesertSol during the competition, and the third is the energy consumption data of 30 Energy Star and 30 non-Energy Star homes of Henderson, Nevada obtained from Shrestha and Kulkarni (2012). The comparison of all three data was done and the results were drawn from this analysis. Finally, the conclusions and recommendations were presented for future research. The methodology used to compare the energy consumption of DesertSol home with local homes in this study is shown in Figure 6.

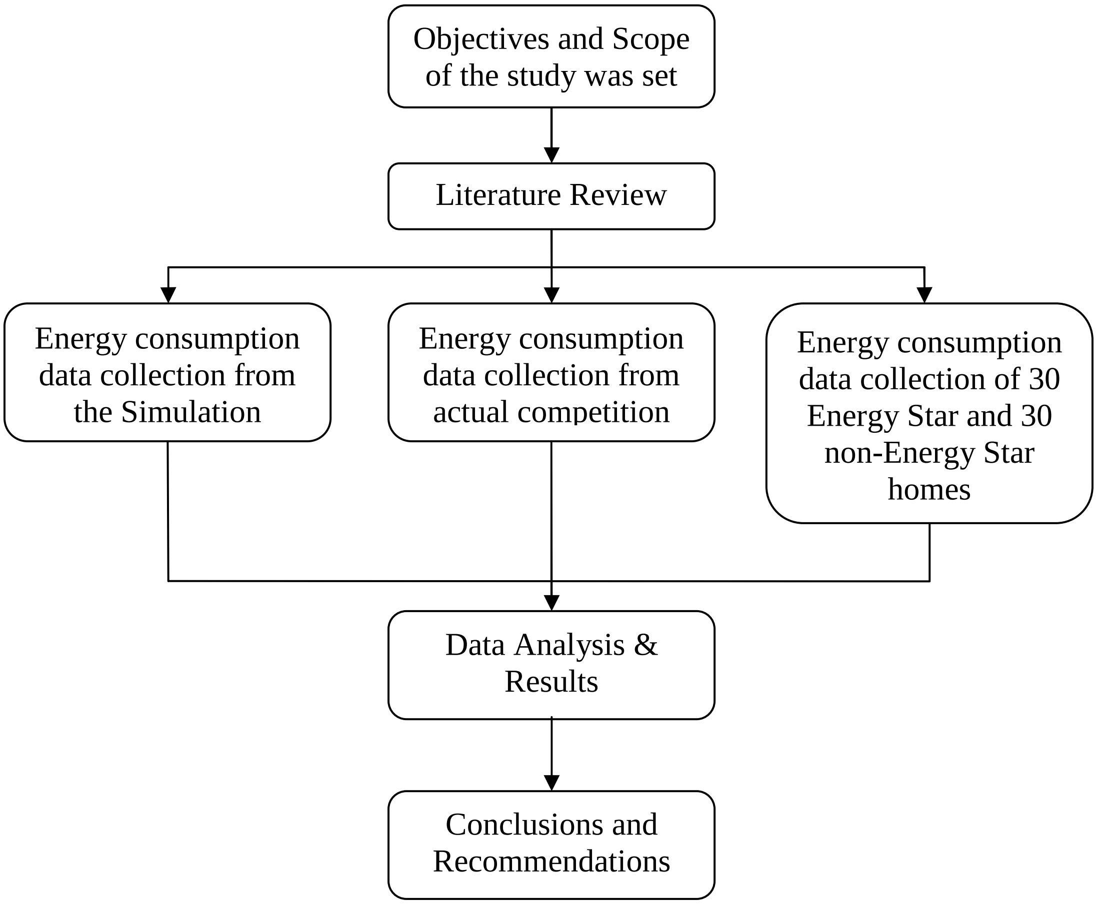

Figure 6. Research Methodology

CHAPTER 4

ENERGY AND COST DATA COLLECTION

4.1 Simulation Energy Data Collection

The energy consumption data of DesertSol from simulation conducted by the mechanical team during the design phase was collected for this study. The details of the simulations conducted during the design phase are described below.

4.1.1 Overall Envelope

Autodesk Vasari was used to model the basic mass elements and parameters. The orientation of the models, the ratio of the glazing, and the roof angles were varied in order to evaluate and decide the design parameters of the home. In addition to this, Revit’s HVAC load tool was used to check the performance of the envelope. BEopt developed by National Renewable Energy Laboratory (NREL) can analyze a building and optimize the cost at the same time. So, this software was used to find the optimum point between the cost and the elements of the building. From the simulation, the R values of the envelope were determined for efficient performance of the home. The R values of the ceiling, wall, and floor were determined to be 55, 30, and 45 respectively.

4.1.2 Energy Consumption

The estimated electricity consumption by the different components of the home for the competition period and for a year was found from the simulation. The expected usage hours/week for the annual electricity consumption and total usage time during the competition period is also listed in Table 3.

Table 3. Estimated Electricity Consumption

Appliance	**Rated Power Consumption (Watts)**	**Annual**		**Competition Period**	
		Usage (Hours/Week)	**Electricity Consumption (kWh)**	**Total Usage (Hours)**	**Consumption During Competition (kWh)**
Refrigerator/Freezer	410	168	3581	199.5	81.79
Dishwasher	1000	4	208	12.5	12.5
Oven	2200	3	343	12	26
Stove	3600	3	562	12	43
Clothes Washer	510	8	212	24	12.24
Clothes Dryer	2800	8	1165	24	67.2
Ceiling Fan	30	42	66	42	1
Notebook Computer	40	35	73	34	1
Television	270	35	491	36.5	10
Home Theater	250	35	455	36.5	9
HVAC	750	28	1092	28	21
Lighting	800	19	790	19	15
Water Heater	12000	2	1248	8	96
Total			10286		395.73

4.1.3 Photovoltaic Simulation

Simulation of the Photovoltaic (PV) system was done using PVsim to determine the size of the PV system that meets the annual electric load of the home. The simulation of the PV panels for Las Vegas, Nevada and Irvine, California was done. The input parameters for the simulations are as shown in Table 4. Simulation of the PV system was done using Typical Meteorological Year 3 (TMY3) data.

Table 4. Simulation Parameters for Two Locations

Description	**Las Vegas, Nevada**	**Irvine, California**
Geographical Site	Las Vegas McCarran International Airport	Santa Ana John Wayne Airport
Latitude	36.08 ^{o}N	33.82 ^{o}N
Longitude	115.17 ^{o}W	118.1 ^{o}W
Elevation	664 m	17 m

The two modules were simulated separately as the orientations of the two modules were different. The simulation parameters for Module A and Module B for both Las Vegas, Nevada and Irvine, California were as shown in Table 5.

Table 5. Simulation Parameters for Module A and Module B

Description	**Module A**	**Module B**	**Total**
Number of PV Modules	9	21	30
Module Area	11.2 m^2	26.1 m^2	37.3
Cell Area	9.6 m^2	22.5 m^2	32.1
Array Tilt	11^o	11^o	-

From the simulation performed, the solar radiation data as well as energy produced by the PV panels for both locations were determined. Simulation results showed that a total energy of 11,956 kWh/yr was produced by the PV panels in both modules for Las Vegas, Nevada whereas a total energy of 10,956 kWh/yr was produced by the panels in both modules for Irvine, California (Table 6).

Table 6. Solar Radiation and Energy Produced

Description	**Las Vegas**		**Irvine**	
	Module A	**Module B**	**Module A**	**Module B**
Average Solar Radiation ($kWh/m^2/day$)	6.14	6.18	5.26	5.36
Energy Produced by the PV panels (kWh/yr)	3626	8330	3286	7670
Total Energy Produced (kWh/yr)	11956		10956	

Simulation was also done to calculate the energy required for cooling and heating purposes in the home. In addition to this, simulation of the solar thermal collector system was also performed to find the optimum angle of tilt for the collectors so that the demand of both domestic water heating and radiant heating could be met. From this it was found that the optimum angle of tilt for the solar thermal collector system is 51 degrees. Moreover, simulation of the hydronic radiant floor heating system was also done. The simulation results showed that when the outdoor temperature was 40^oF, the total radiant load was 4,221 Btu/hr.

4.2 Real Competition Site Data Collection

The Solar Decathlon 2013 rules required some specific tasks that needed to be performed for all the measured contests. The comfort zone, hot water, appliances, home entertainment, and energy balance contests were the measured contests. The tasks required in these contests were designed to resemble the activities that would be performed in a typical home. The energy consumption data of the house in this study are based on these requirements of the contest and tasks performed during the contest. The contest period during which the data for this study was collected started from 11:00 am October 3, 2013 to 11:00 am October 11, 2013.

4.2.1 Comfort Zone Data

The temperature and humidity inside the home were measured in this contest. For this purpose, Point Six Wireless Temperature/Humidity Probe Model 3009-02-V5 sensors were used. In the case of temperature, the indoor temperature had to be maintained between 71^{o}F (22.2^{o}C) and 76^{o}F (24.4^{o}C). The HVAC systems were operated to maintain this temperature. Two thermal zones in the house were identified and the temperature of each zone was measured. The temperature of the house was measured for every 15-minute interval during the entire contest period. On the other hand, for the humidity subcontest, the interior relative humidity had to be maintained below 60.0%. The humidity of the zone that varied the most from the target humidity (60.0%) was recorded and was used for scoring by the organizers.

4.2.2 Hot Water

Hot water was drawn from the shower of the bathroom to replicate the washing and bathing that occurs in a regular house in a typical day. This contest measures the ability of the house to supply adequate amounts of hot water required for these daily purposes. One draw was done each day of the competition making a total of eight draws. In each draw 15 gallons (56.8 L) of hot water was drawn. The contest required that the water should be drawn within 10 minutes and the average temperature of this water has to be at least 110^o F (43.3^o C).

4.2.3 Appliances

This contest was designed to see whether the appliances in the house are capable of performing as they should on a regular basis in a normal occupied house. The refrigerator and the freezer were operated 24 hours a day during the entire contest period. The temperature of the refrigerator and the freezer was measured using Point Six Wireless RTD sensor Model 3009-20-V4 and 1000-21. The main target during the competition period was to maintain the interior temperature of the refrigerator between 34.0^o F (1.11^o C) and 40.0^o F (4.44^o C) to get the full points. In the case of the freezer, the interior temperature of the freezer was measured in order to check if the temperature was between -20.0^o F (-28.9^o C) and 5^o F (-15^o C). The automatic defrost function was disabled while the temperature of the freezer was being measured as required by the competition.

In addition to the refrigerator and the freezer, the clothes washer, dryer, and the dishwasher were also operated. A total of eight loads of laundry were washed in the clothes washer during the entire contest period. One load of laundry is defined by the organizers as six bath towels supplied by the organizer. The clothes washer was operated automatically and was operated for at least one wash and rinse cycle. Moreover, the clothes dryer was also operated to dry a load of laundry. So a total of eight loads of laundry were dried during the data collection period. The clothes' drying was completed within a specified period of time as required by the competition. Furthermore, the dishwasher was also operated through a complete, uninterrupted cycle specified by the organizer. The competition required that the dishwasher should be operated for at least one wash and rinse cycle; and the temperature inside the dishwasher should reach 120^{o}F (48.9^{o}C) at some point during the cycle. To measure this temperature, Omega Nonreversible Temperature Label Model TL-5-105-10 was used.

4.2.4 Other Energy Consuming Activities

The home entertainment contest had five subcontests which also contributed to the energy consumption during the competition period. The first subcontest, lighting, required all the interior and exterior lights to be turned on during specified periods of time so all the lights were turned on during this period. The lights were turned on during the entire contest period from 7:30 pm to 10:30 pm as required by the contest. In order to perform the task in the second subcontest, cooking, 5.00 lb (80 oz or 2.268 kg) of water was vaporized using the kitchen appliances during the specified period of time. This was done for 5 days during this period. In addition to this, as required by the third subcontest, two dinner parties were also held during the competition period on October 3 and October 5 from 7:00 pm to 11:00 pm which also required cooking inside the home. Moreover, the television (TV) and computer were operated for a specified period of time as required by the fourth subcontest. Furthermore, a movie night was hosted as per the requirement of the fifth and the last subcontest. The movie night was hosted on October 4 from 7:00 pm to 10:30 pm.

The net energy consumption data of the home for every 15 minutes during the entire contest period was collected from the spreadsheet provided by the organizers (DOE) to the team. This net energy data was used by the organizers for scoring in the Energy Balance Contest. But for the purpose of this study, the sum of the net energy of

24 hours for 7 days has been calculated except for the first and the last day of the contest (Table 7). On the first day and the last day of the contest only 13 hours and 11 hours respectively were taken into consideration, since the contest started at 11:00 am on the first day and ended on 11:00 am on the last day. A net energy of 97.887 kWh was observed during the contest period; this indicates that the home was capable of producing 97.887 kWh of extra energy than it required.

Table 7. Energy Production, Consumption & Net Energy During the Competition Period

Day	**Time**	**Hours**	**Energy Produced (kWh)**	**Energy Consumed (kWh)**	**Net Energy (kWh)**
October 3, 2013	11:00 AM – 11:45 PM	13	18.573	9.557	9.016
October 4, 2013	12:00 AM – 12:00 PM	24	33.838	14.366	19.472
October 5, 2013	12:00 AM – 12:00 PM	24	35.388	19.252	16.136
October 6, 2013	12:00 AM – 12:00 PM	24	33.944	17.565	16.379
October 7, 2013	12:00 AM – 12:00 PM	24	29.637	18.473	11.164
October 8, 2013	12:00 AM – 12:00 PM	24	32.025	14.284	17.741
October 9, 2013	12:00 AM – 12:00 PM	24	9.248	22.994	-13.746
October 10, 2013	12:00 AM – 12:00 PM	24	34.063	10.814	23.249
October 11, 2013	12:00 AM – 11:00AM	11	9.357	10.881	-1.524
	Total		236.073	138.186	97.887

4.3 Energy Star and non-Energy Star Homes in Henderson, Nevada

Shrestha and Kulkarni (2013) conducted a survey on single-family Energy Star and non-Energy Star homes to identify the factors affecting the energy consumption of residential buildings. The authors distributed questionnaires to 110 single-family homes, out of which 55 were Energy Star homes and 55 were non-Energy Star homes. The authors received responses from 79 homes, out of which 30 homes were Energy Star homes and 30 homes were non-Energy Star homes, and the rest of the responses from 19 homes were incomplete. Thus, the authors considered only 30 Energy Star and 30 non-Energy Star homes in their study from which the complete responses were received.

In this study, the questionnaire was prepared in four sections. The first section of the questionnaire consisted of questions related to the total area of the home, number of household members, and type of windows. In addition to this, questions were also asked if the home had an attached garage or not, if the garage was heated/air conditioned or not, and also if the home was rented or owned. The second section of the questionnaire consisted of questions related to age, fuel type (electricity or natural gas), and the frequency of use of home appliances such as stove, oven, microwave, dishwasher, and the washing and clothes dryer. Moreover, the third section included questions on age, fuel type (electricity or natural gas), the frequency of use of heating equipment, and typical thermostat temperature setting during winter. The fourth and the last section consisted of age, type, and the frequency of use of air conditioner, use of ceiling fans and typical temperature setting during the summer. Table 8 shows the characteristics of Energy Star and non-Energy Star homes used for this study.

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Table 8. Characteristics of Energy Star and non-Energy Star Homes

(Adopted from Shrestha and Kulkarni, 2013)

Housing unit characteristics	**Energy Star**	**non-Energy Star**
Floor space area (m^2)	110 – 321 (1,200 – 3,500 ft^2)	101 – 312 (1,100 – 3,400 ft^2)
Number of household members	1 – 5	1 – 6

However, for the purpose of this study, the mean energy consumption of both the Energy Star and non-Energy Star homes was extracted from this study and was used to compare with the energy consumption data of DesertSol (Table 9). The total energy consumption includes both the electricity and natural gas consumption by the homes

Table 9. Average Energy Consumption of Energy Star and non-Energy Star Homes

(Adopted from Shrestha and Kulkarni, 2013)

Description	**Energy Star (N = 30)**	**non-Energy Star (N = 30)**
Average annual electricity consumption [kWh/ft^2]	4.419	5.049
Average annual natural gas consumption [kWh/ft^2 ($therms/ft^2$)]	7.385 (0.252)	7.209 (0.246)
Total average annual energy consumption [kWh/ft^2]	11.804	12.258

4.4 Cost of the Home

The affordability contest in the competition challenges the teams to make their homes affordable in addition to the architecture, energy efficiency, and other criterion of the construction. In this contest, each home is judged based on its estimated cost. Teams were awarded full points, 100, if the cost of their home was $250,000 or less and zero points if the cost was $600,000 or more. The scores for the homes in between these costs were awarded based on a curve set by the organizers. The cost estimation done by the team during the initial stage of the designing phase showed that the cost of DesertSol was $316,141. Changes in the design were made to reduce the cost of the home and get high scores in the affordability contest. After these changes were made, the final cost of the home estimated by the organizers was $298,629 ($372.36 per sqft). The home was scored based on this cost in the affordability contest. The unit costs in the cost estimation data included labor, material, equipment costs, and also subcontractor’s overhead and profit. In addition to this, the final cost also included a contingency of 2.5%; however, no markups (general conditions, overhead, and profit) were included in the cost. Table 10 shows the estimated cost of the major components of the home.

Table 10. Cost Estimation of the Major Components of the Home

Description	Estimated Cost
Superstructure	
Floor Construction	$19,921
Roof Construction	$17,382
Exterior Closure	
Exterior Walls	$26,022
Exterior Windows	$7,543
Exterior Doors	$10,910
Mechanical	
Heat Generating Systems	
Including Solar Thermal Hot Water Tank, Solar Tube Collector, Solar Flex Piping, Solar Thermal Loop Pump	$8,490
Cooling Generating System	
Including Radiant Floor Pipes, Heating Manifold, Expansion Tank, Valves, Energy Recovery Ventilator, Mini Split with Evaporative/Condensing/Refrigerant Piping	$19,832
Commercial Equipment (Appliances)	
Clothes Washer, Dryer, Refrigerator/Freezer, Oven, Cooktop, Dishwasher, and Exhaust Hood	$12,277
Electrical Distribution	
PV System and Inverter (30 units)	$27,300
Other (100A Service, 200A Service, and miscellaneous)	$7,732

CHAPTER 5

RESULTS

The collected data of the simulation, the actual competition, and the 30 Energy Star and 30 non-Energy Star homes were analyzed. A comparison of the energy consumption data obtained during the simulation, the actual competition, and from the previously conducted questionnaire survey of 30 Energy Star and 30 non-Energy Star homes was done.

The energy consumption data obtained from the simulation, the actual energy production and consumption data during the competition were also converted to kWh/ft^2 by dividing the energy consumption by the square foot area of the home. The summary of the energy data of DesertSol, Energy Star homes, and non-Energy Star homes is given in Table 11.

From the actual energy production and consumption data of DesertSol obtained during the competition, the annual energy production and consumption data were calculated. This was done by dividing the competition's data by 8 days (the duration of the competition) and multiplying by 365 days/year. From this, the actual annual energy produced and actual annual energy consumed were obtained to be 19.73 kWh/ft^2/yr and 11.55 kWh/ft^2/yr respectively.

Table 11. Summary of Energy data of DesertSol and Energy Star and non-Energy Star Homes

	DesertSol (Irvine, California)				**Local homes of Henderson, Nevada**	
	Simulation		**Actual**		**Energy Star homes**	**non-Energy Star homes**
	Annual (kWh/ft^2/yr)	**Competition (kWh/ft^2)**	**Annual (kWh/ft^2/yr)**	**Competition (kWh/ft^2)**	**(N=30) (kWh/ft^2/yr)**	**(N=30) (kWh/ft^2/yr)**
Energy produced	20.06	-	19.73	0.43	-	-
Energy consumed	18.84	0.72	11.55	0.25	11.80	12.26
Net Energy	1.22	-	8.18	0.18	-	-

From the data of DesertSol, obtained during the actual competition period, it was observed that a net energy of 0.18 kWh/ft^2 was produced during the competition. This shows that DesertSol is a net zero energy house, which means that DesertSol produced more energy during the competition period than it required.

5.1 Comparison between the Actual Energy and the Simulated Energy Data of DesertSol

The actual net energy of the home during the contest period in Irvine, California is compared with the net energy of the simulation of the home for the same location. The net energy produced per year is calculated from the simulation data. The net energy produced per year is calculated from the energy produced per year and the energy consumed per year (Table 12). This is done by subtracting the energy consumed per year from energy produced per year. This net energy per year is then converted to the net energy during the competition by dividing by 365 days and multiplying by 8 days, which is the duration of the competition. This net energy during the competition obtained from the simulation is compared with the net energy of the home during the actual competition.

Table 12. Comparison of Net Energy of DesertSol During the Competition

Description	**Simulation**		**Actual**	
	Annual ($kWh/ft^2/yr$)	**Competition (kWh/ft^2)**	**Annual ($kWh/ft^2/yr$)**	**Competition (kWh/ft^2)**
Energy Produced	20.06	-	19.73	0.43
Energy consumed	18.84	0.72	11.55	0.25
Net Energy	1.22	-	8.18	0.18

From this comparison it was found that in the case of the annual energy consumption data, DesertSol would consume nearly 39% less energy than the simulated results. The simulation results showed that the home would consume 18.84 $kWh/ft^2/yr$ energy during the competition; however, only 11.55 $kWh/ft^2/yr$ consumption was observed from the data of the competition period.

Also, in the case of net energy data, a net energy of 0.18 kWh/ft^2 was produced during the competition period. A reason for this variation in the simulated and actual data could be the extra margin considered in the energy consumption data during the simulation for the competition period.

5.2 Comparison between the Actual Energy Consumption Data of DesertSol and the 30 Energy Star and 30 non-Energy Star Homes in Henderson, Nevada

A comparison of actual energy consumption data of DesertSol and the 30 Energy Star homes and 30 non-Energy Star homes in Henderson, Nevada was done (Table 13). The average annual energy consumption per square feet of both homes was compared. From this comparison it was observed that the annual energy consumed by DesertSol was 11.55 kWh/ft^2/yr and the average annual energy consumed by the Energy Star homes and non-Energy Star homes in Henderson, Nevada was 11.80 kWh/ft^2/yr and 12.26 kWh/ft^2/yr respectively. However, it should be noted that the energy consumption of DesertSol was calculated for the weather of Irvine, California for eight days of the competition only, whereas the energy consumption of the Energy Star homes and non-Energy Star homes collected were for the weather of Henderson, Nevada for the period of one year. From this comparison, it was observed that DesertSol consumed 2% less energy than the Energy Star homes and nearly 6% less energy than the non-Energy Star homes. This comparison shows that DesertSol is energy efficient than both the Energy Star homes and non-Energy Star homes being analyzed by Shrestha and Kulkarni (2013).

Table 13. Actual Annual Energy Consumed by DesertSol vs. Energy Star and non-Energy Star Homes

Description	**DesertSol (Irvine, California)**	**Local homes of Henderson, Nevada**	
	Actual ($kWh/ft^2/yr$)	**Energy Star homes (N=30) ($kWh/ft^2/yr$)**	**non-Energy Star homes (N=30) ($kWh/ft^2/yr$)**
Energy produced	19.73	-	-
Energy consumed	11.55	11.80	12.26
Net Energy	8.18	-	-

5.3 Comparison between the Simulated Energy Consumption Data of DesertSol and the 30 Energy Star and 30 non-Energy Star Homes in Henderson, Nevada

A comparison between the simulated energy consumption of DesertSol and the average annual energy consumption of 30 Energy Star homes and 30 non-Energy Star homes was also done (Table 15). From this comparison it was observed that DesertSol consumed 18.84 $kWh/ft^2/yr$ and Energy Star and non-Energy Star homes consumed 11.80 $kWh/ft^2/yr$ and 12.26 $kWh/ft^2/yr$ respectively. However, in this case also, it should be noted that the simulation of DesertSol was done for the weather of Irvine, California, whereas the energy consumption data of the Energy Star and non-Energy Star homes was for the weather of Henderson, Nevada. From this comparison it was observed that

DesertSol consumed 37% more energy than the Energy Star homes. Also, it was observed that DesertSol consumed 35% more energy than the non-Energy Star homes.

Table 14. Simulated Annual Energy Consumed by DesertSol vs. Energy Star and non-Energy Star Homes

Description	**DesertSol (Irvine, California)**	**Local homes of Henderson, Nevada**	
	Simulation (kWh/ft^2/yr)	**Energy Star homes (N=30) (kWh/ft^2/yr)**	**non-Energy Star homes (N=30) (kWh/ft^2/yr)**
Energy produced	20.06	-	-
Energy consumed	18.84	11.80	12.26
Net Energy	1.22	-	-

5.4 Limitations

The actual energy consumed by DesertSol in the weather of Las Vegas could not be obtained because the home was not completed in Las Vegas to the extent that the data could be collected. The data of DesertSol was obtained for the weather of Irvine, California and was compared with the energy consumption data of the 30 Energy Star and 30 non-Energy Star homes in the weather of Henderson, Nevada. The energy consumption data of DesertSol in the weather of Las Vegas would be more comparable.

The data collection period of DesertSol was only for 8 days, the competition period, whereas, the data of the Energy Star and non-Energy Star homes was for a one-year period. A longer period of data collection, at least a year, could provide more realistic data that could be compared with the Energy Star and non-Energy Star homes.

In addition to this, the input parameters were also not same. The simulation was targeted towards the competition, so the simulation was based for the weather of Irvine, California and was also overrated. On the other hand, the actual data during the competition was based on the activities required by the competition. Even though the activities required by the competition were assumed to be the activities a normal household would perform in a typical home, the data of the home in an occupied condition would give more accurate data.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

The purpose of this study was to describe the design and construction features of DesertSol and study its energy consumption. Moreover, comparison of energy consumption of DesertSol with 30 Energy Star and 30 non-Energy Star homes in Henderson, Nevada was the other objective of the study. So, the conclusions and recommendations derived from the above study are described below.

6.1 Conclusions

From the conducted study, it can be concluded that DesertSol is a net zero energy home. DesertSol produced 0.18 kWh/ft^2 of more energy than it consumed during the competition period. It was also observed that DesertSol would produce a net energy of 8.18 $kWh/ft^2/yr$ in a year. Furthermore, it was also observed that DesertSol produced as much energy as it consumed during the competition as anticipated from the simulation.

Moreover, from the comparison of the simulated energy data and actual energy data for the competition period, it was observed that DesertSol performed better during the competition than it was expected from the simulation results. In addition to this, it was observed that DesertSol would consume 39% less energy in a year than expected from the simulation results.

Furthermore, the comparison of the actual annual energy consumption data of DesertSol with 30 Energy Star homes and 30 non-Energy Star homes in Henderson, Nevada showed that DesertSol consumed 2% less energy than the Energy Star homes and nearly 6% less energy than the non-Energy Star homes. In addition to this, the comparison of the simulated energy consumption data of DesertSol with average annual energy consumption data of Energy Star and non-Energy Star homes showed that the DesertSol consumed 37% more energy than the Energy Star homes and 35% more energy than the non-Energy Star homes. The simulation was targeted for the competition period, so the energy consumption data was overrated to be on a safer side. This was one of the reason that DesertSol was observed to consume more energy than the Energy Star homes and non-Energy Star homes.

The 2x6 framing technique placed at 24-inches on-center, which is different from the conventional 2x4 framing placed at 16-inches on-center allows more space for insulation on the wall. The overhang shade screens on both modules reduce the amount of heat entering the home during the summer. In addition to this, the digitally-fabricated operable shade screen on the patio space of Module A provide shade during the summer and could be opened during the winter to allow the sunlight enter into the home. Moreover, these screens allow the heat to escape during the night time.

The tighter envelope and the Tyvek Stucco Wrap, used to wrap the entire home for air and moisture protection, aided in the energy efficiency of the home. The one-inch foil faced rigid foam insulation placed on top of the homewrap reflects maximum sunlight and helps in reducing the temperature of the home envelope. Furthermore, the 7/8-inch hat channels with holes on the sides and arranged in a zigzag pattern allowed the hot air trapped between the rainscreen and the rigid foam to escape. This controls the temperature of the exterior of the home, which ultimately affects the interior temperature of the home. The double glazed low-e glazing with argon filled in between also contributed in an efficient envelope.

The main advantage of the ductless minisplit heat pump system used in the home is that there is no chance of leakage of the conditioned air, unlike the conventional ducted air conditioning system usually installed in the attic of the home. The two separate indoor units, each used in two modules, allow one unit to be turned off if the space conditioning is not required at particular time. This reduces the energy consumption of the home. The solar thermal collector system uses the heat gained from the sun to heat the water, which is used both for the radiant floor heating purpose and domestic hot water purposes. Thus this system is an efficient way to heat the home as well as for hot water purposes. Lastly, the Energy Star appliances used in the home is also one of the factors in the reduction of the energy consumption.

6.2 Recommendations

Based on the results of the study, there are some more areas that could be a subject of further research. Data of DesertSol was collected for the competition period of 8 days in the weather of Irvine, California. So, for future studies, a longer period of time at least a year could be considered to study the energy consumption as well as the consistency of the performance of the home in different seasons. Also, it is recommended that the energy consumption data of the home in the same weather as that of the homes being compared should be collected so that a reasonable comparison could be made. Moreover, the data of the home could be collected in an occupied condition so that the energy consumption by the home could be compared to a typical occupied home. This would give the real performance of the home.

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