5-1-2012

Assessing the Engineering Performance of Affordable Net-Zero Energy Housing

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Graduate School ETD Form 9
(Revised 12/07)

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ASSESSING THE ENGINEERING PERFORMANCE OF AFFORDABLE NET-ZERO ENERGY HOUSING

For the degree of Master of Science

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ASSESSING THE ENGINEERING PERFORMANCE OF AFFORDABLE NET-ZERO ENERGY HOUSING

A Thesis

Submitted to the Faculty

of

Purdue University

by

Jordan P. Wallpe

In Partial Fulfillment of the

Requirements for the Degree

of

Master of Science

May 2012

Purdue University

West Lafayette, Indiana

To our Heavenly Father and to my loving parents.

ACKNOWLEDGMENTS

To the student members on the 2011 Purdue INhome Solar Decathlon Team, especially Kevin Rodgers and Sarah Miller, well-done. To the rest of the student managers, Eric Holt, Lee Causey, Derek Kultgen, McKenna Regan, Mallory Schaus, Matthew Hebdon, and Elizabeth Price; what valuable and memorable experiences we had during our great endeavor! Boiler Up and Hammer Down!

To all contributing faculty at Purdue University, especially Brian Loss, Mark Shaurette, Clark Cory, and Otie and Rosemary Kilmer. Thank you for your professional guidance along the way.

To William J. Hutzel, thank you for all of the hard work and commitment in making the INhome a reality. Most importantly, thank you for the opportunity given to me.

To the Applied Energy Laboratory in Knoy Hall. Thanks for all the great memories and long days. Your ability to bring so many students, faculty members, and visitors together was extremely convenient and much appreciated.

And finally for all of those who I did not mention. Those who helped with the INhome one way or another, either personally visiting or helping us out along the way. You're thoughtfulness and support was very much valued. Thank you.

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ABSTRACT

Wallpe, Jordan P., Purdue University, May 2012. Assessing the Engineering Performance of Affordable Net-Zero Energy Housing. Major Professor: William J. Hutzel.

The purpose of this research was to evaluate affordable technologies that are capable of providing attractive, cost-effective energy savings to the housing industry. The research did so by investigating the 2011 Solar Decathlon competition, with additional insight from the Purdue INhome. Insight from the Purdue INhome verified the importance of using a three step design process to design a net-zero energy building. In addition, energy consumption values of the INhome were used to compare and contrast different systems used in other houses.

Evaluation of unbiased competition contests gave a better understanding of how a house can realistically reach net-zero. Upon comparison, off-the-shelf engineering systems such as super-efficient HVAC units, heat pump hot water heaters, and properly designed photovoltaic arrays can affordably enable a house to become net-zero. These important and applicable technologies realized from the Solar Decathlon will reduce the 22 percent of all energy consumed through the residential sector in the United States. In conclusion, affordable net-zero energy buildings can be built today with commitment from design professionals, manufacturers, and home owners.

CHAPTER 1. INTRODUCTION

The following research experiment was conducted to find and prioritize technologies regarding affordable solar housing. This research is significant because it was a realistic evaluation of the built environment. More specifically, it realistically evaluated the engineering performance of world-class solar housing. The purpose, scope, and significance of evaluating the engineering performance of affordable net zero-energy housing will be discussed in this chapter. Key definitions, assumptions, limitations, and delimitations associated with this research will be explained as well.

1.1. Statement of Purpose

The purpose of this research is to evaluate affordable technologies that are capable of providing attractive, cost-effective energy savings to the housing industry. The research did so by investigating the 2011 Solar Decathlon competition, with additional insight from the Purdue INhome. Evaluation of the competition contests gave a better understanding of how a house can reach net-zero. Ultimately, these technologies could be implemented throughout the residential sector to reduce the overall amount of energy consumed.

In 2005, the residential sector in the United States consumed 21.21 quadrillion Btu's, or 22.4 percent of all energy consumed in the United States. Of those 21.21 quadrillion Btu's, 40 percent was consumed through electricity end-uses, totaling 125 billion dollars (U.S. Energy Information Administration, 2009). To put this in perspective, if all electricity consumed by the housing sector came from coal, the coal pile would fill an entire NFL football field several hundred feet tall. This statistic helped drive the formation of the Solar Decathlon, a biennial solar-housing competition sponsored by the United States Department of Energy.

The Solar Decathlon is a worldwide competition where university students compete to design, build, and test energy-efficient, net-zero homes. By definition, a net-zero energy house annually produces as much electricity as it consumes (Torcellini, Pless, Deru, and Crawley, 2006, pg.4). A team from Purdue University was selected as one of 20 student-led teams to design, build, and showcase a house called the INhome. Team Purdue's approach with the INhome was to make an affordable and practical net-zero energy home that was well suited for today's Midwestern housing market.

1.2. Scope

This research utilized the 2011 Solar Decathlon as a platform of identifying successful building design approaches. This was a valid experimental platform because the Solar Decathlon has developed a reputation of identifying technologies applicable to the next generation of solar living in America. With the 2011 competition, several different design approaches were evident in each house stemming from a consortium of intelligent and creative minded students. Intense commitment was necessary, as the competition demanded two years of preparation from all teams. In return, the competition's successful historical impact and rigorous preparation provided a very solid research platform.

As the competition name implies, the Solar Decathlon 2011 had 10 equally-weighted contests in which each house competed in. The competition had both quantitative and qualitative contests. The quantitative, or measured contests, were Comfort Zone, Hot Water, Appliances, Home Entertainment, and Energy Balance. Likewise, the subjective contests were Architecture, Market Appeal, Engineering, Communications, and Affordability. All teams could earn up to 100 points for each of the contests.

Of the 10 contests, six of them were most valuable to this research as seen in Table 1.1. The four quantitative contests (left-hand column) most visited were the Energy Balance, Hot Water, Comfort Zone, and Appliance Contests. Engineering and Affordability Contests gave valuable information through a qualitative approach as highlighted in the right-hand column.

Table 1.1.

Significant 2011 Solar Decathlon Contests.

Measured Contests	**Juried Contests**
Appliances	Engineering
Hot Water	Affordability
Comfort Zone	Market Appeal
Energy Balance	Communications
Home Entertainment	Architecture

The Hot Water, Comfort Zone, and Appliance Contests gave valuable insights on individual system performance. System performance with respect to energy consumption was then indirectly measured through the Energy Balance Contest. The Engineering Contest highlighted design initiatives and qualities that scored best. Lastly, the total estimated value of each house and the individual cost of each system was accessed through the Affordability Contests. All of these contests were evaluated to find a more affordable solution of reaching net-zero in residential buildings.

1.3. Significance

The Solar Decathlon showcases affordable, solar living on a national stage in order to encourage Americans to reduce the United States' dependence on fossil fuel energy. Moreover, the Solar Decathlon also equips participating students with powerful work skills necessary to expand our country's clean energy workforce. By doing so, the negative effects of global warming and energy security can be minimized. Lastly, increased energy consumption awareness is elevated by exhibiting the Solar Decathlon to homeowners nationwide.

Almost a quarter of the energy consumed in the United States was used by residences in 2009. Unfortunately, this statistic and the cost to end-users will most likely continue to increase. In fact, the average nominal retail price of electricity in the residential sector was a little above $0.02/kWh in 1960 and was hovering around $0.11/kWh in 2010 (U.S. Energy Information Association, 2010). History indicates that energy consumption and retail cost have always progressively increased, with minor increases and decreases along the way. The expected rising cost of electricity poses a threat to many homeowners' ability to keep their existing quality of living ongoing.

Electricity in a majority of the U.S. is currently at a reasonably low price. Exceptions are costal and remote geographical locations as seen in Figure 1.1. More specifically speaking, the cost of residential electricity in Indiana and surrounding states is near $0.08/kWh. The average cost of U.S. residential electricity in 2010 was $0.983/kWh.

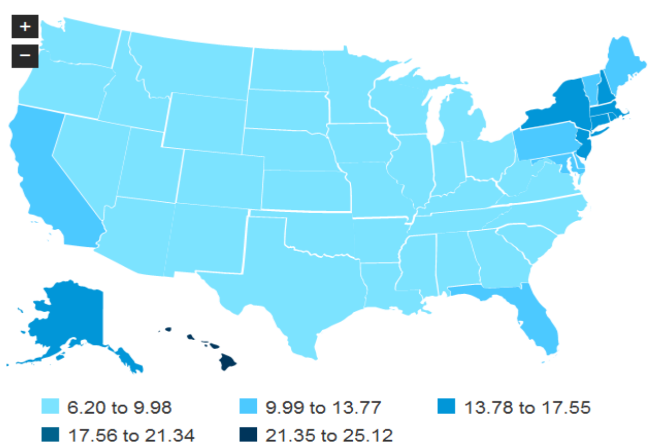

Figure 1.1. State Retail Electricity Profile Map 2010. (U.S. EIA, 2011).

This low cost electricity does not necessitate the average homeowner to find alternative ways of living. The quality of proven widespread knowledge over "net-zero energy housing" is gradually reaching homeowners and builders throughout the U.S., but more specifically, the Midwest. Interest in becoming "environmentally friendly" is slowly growing amongst all age categories, from the elderly to young adults. There are well designed case studies throughout the Midwest that offer alternative ways of living, but do not thoroughly explain what systems offer the most affordable ways of net-zero energy living. That being said, this research focused on finding affordable energy saving designs and technologies that were utilized in 2011 Solar Decathlon houses. Many of these energy saving designs and technologies were evident in the INhome design as well.

The overarching design initiative of the Purdue INhome was not to forgo modern comforts of today's living, but only minimize energy consumption and then maximize energy production. The INhome offered homeowners a new perspective to solar housing by integrating established building techniques with new and innovative technologies. It also eliminated the monthly electric utility bill. The types of technologies and designs found through this research are valuable impacts that must be considered even where electricity is currently low-cost.

This research answers this most important question of, "How does the engineering performance of affordable, net-zero energy housing contribute to the overall house performance in the U.S Department of Energy Solar Decathlon 2011?" This approach to construct affordable, solar-powered houses was evaluated by the contest results from all 19 teams in the competition. The goal of this research was to identify key components that are cost-effective and contain energy conserving characteristics. Several key components and designs to building a net-zero house have been recognized.

1.4. Definition of Key Terms

AC – alternating electric current

DC – direct electric current

D.O.E – United States Department of Energy

Net Zero Building– The ability of a building to annually produce as much electricity as it consumes (Torcellini, Pless, Deru, and Crawley, 2006, pg.4).

net-zero – shortened use of the term Net Zero Building

Energy Model – a computer program that accurately predicts energy consumption of a building.

ERV – energy recovery ventilator

HVAC – heating, ventilation, and air conditioning

INhome – Team Purdue's submission to the United States Department of Energy Solar Decathlon 2011. The name comes from "Indiana Home."

kW – kilowatt, a common unit of power in the SI system

kWh – kilowatt-hour, the standard unit of energy in the SI system

PV – photovoltaic

SD – Solar Decathlon

1.5. Assumptions

The assumptions for this project will include:

- All contest data collection acquired during the Solar Decathlon 2011 was un-altered by each individual team and carefully monitored and recorded by competition organizers.

- The data collected during the 10 consecutive-day period is an accurate representation of net-zero energy homes.

1.6. Limitations

This research is limited by the following:

- The research analyzes only similar houses that competed in the Solar Decathlon 2011 and each house's official contest results.
- The affordability of a solar net-zero energy house will be determined by contest results only.

1.7. Delimitations

The delimitations for this project include:

- The affordability of a net-zero energy solar house will not consider incentives and pricing associated with different geographical locations.
- The research will only focus on solar energy. No other alternative forms of energy will be used.

1.8. Summary

The importance of discovering affordable, net-zero energy housing was introduced in this research. By evaluating innovative house designs from university students worldwide who competed in the 2011 Solar Decathlon, several key themes and technologies were discovered. Providing the information found in this research to homeowners and builders will ultimately reduce the amount of energy consumed by the residential sector and help mitigate global warming. The following chapter is reflective of currently available examples and research that have already begun to transform residential buildings.

CHAPTER 2. REVIEW OF RELEVANT LITERATURE

Many different types of resources were examined to identify currently available sources within this area of study. The author found resources by using online databases, trade magazines, newspapers, master's thesis, and books. Resource quality was taken into account while building arguments towards research questions.

The main focus of this review was to find literature that expressed what systems and designs that had an overall impact of reducing energy consumption in residential buildings. More specifically, what engineering strategies, systems, and technologies greatly increase overall house performance and why? For the most part, the references offered examples of case studies suggesting the builder, designer, and homeowner build a certain way. Unfortunately, not all of these research articles gave an in depth analysis of why these decisions were made. Several of these articles could not attest to how being net-zero was affordable. However, one resource in particular, the United States Department of Energy Solar Decathlon, expressed a fundamental goal of making net-zero energy housing affordable. The inaugural Solar Decathlon was held in 2002; and because of its rich tradition the widespread effects of past Solar Decathlons were well utilized for this review.

2.1. Search Areas for Literature Review

To create a complete literature review, several areas for information were identified. To begin, the author found information regarding residential buildings and their energy consumption characteristics. The most visited outlet was the

Purdue University Library. The Library's online database was a useful portal to numerous databases all over the world. For example, having access to other master's research theses proved invaluable due to the knowledge of sustainable building in academia.

In particular, one group of organizations seemed to provide more information while searching through books, articles, and journals. Several governmental organizations have made a sustained effort to promote energy conscientious decisions for U.S. citizens through projects and publications. The U.S. Department of Energy has an overarching mission statement to "Advance the national, economic, and energy security of the United States" (U.S. Department of Energy, 2010). That being said, DOE's research outreach was a pivotal and expansive resource on which to build this research upon.

Nevertheless, several other professional organizations have wholeheartedly made advancements in the development of energy efficient buildings as well. These organizations are progressing new and innovative technology applications in residential buildings nationwide. It is imperative that these technological applications continue to be publicized to the American public through print and online material.

The American Society of Heating, Refrigeration, and Air Conditioning (ASHRAE) has contributed many professional journal articles revealing information about past Solar Decathlon homes and the lessons learned from building feasible, net-zero energy buildings. The ASHRAE Journal mainly focuses on the internal comfort of buildings and how comfort levels can be efficiently obtained. However, several inserts discuss building operation and performance from a whole building basis.

The National Association of Home Builders (NAHB) was also a resource that provided the author with access to research articles and case studies. One of the research findings from an NAHB concluded that three main factors have contributed to the emission of greenhouse gases from residential buildings.

These three factors are utility plants generating electricity from fossil fuels, the age of a house, and human behavior within the house (Emrath & Liu, 2007).

2.2. History of Research Background

Building a home that utilizes the surrounding environment is nothing new. The Greek Philosopher Socrates quoted: “In houses that look toward the south, the sun penetrates the portico in winter, while in summer the path of the sun is right over our heads and above the roof so that there is shade” (Walker, Renne, Bilo, Kutscher, Burch, Balcomb, 2003, pg.236). Socrates recognized what passive design was over 2300 years ago. This is an example of how past knowledge should still be used to optimize houses worldwide. Unfortunately, an easier and cheaper way to build houses was followed throughout time. For example, take a look at the houses in a local neighborhood. A large quantity of the so-called “cookie-cutter” houses could easily be built with energy efficiency and passive design in mind. Many houses have large south facing windows with no shading at all. An easy way to save energy would be to correctly shade the windows to provide shading in the summer and capture the sun’s radiant energy during the winter.

More importantly, the average American home consumes nearly 12,000kWh annually. In 2009, homeowners spent on average $2,100 towards energy expenditures (U.S. Energy Information Association, 2010). Figure 2.1 is a breakdown of energy consumed in a typical American house in 2008. Notice that heating processes, water heating and space heating, consumed 50 percent of all energy. Furthermore, look at all of the small loads that add up over time, consuming energy without the homeowner even noticing. Fortunately, there are many ways to save energy easily in today’s residential sector. Manufacturers are making great strides in energy saving advancements in lighting, water heating, HVAC, and appliances.

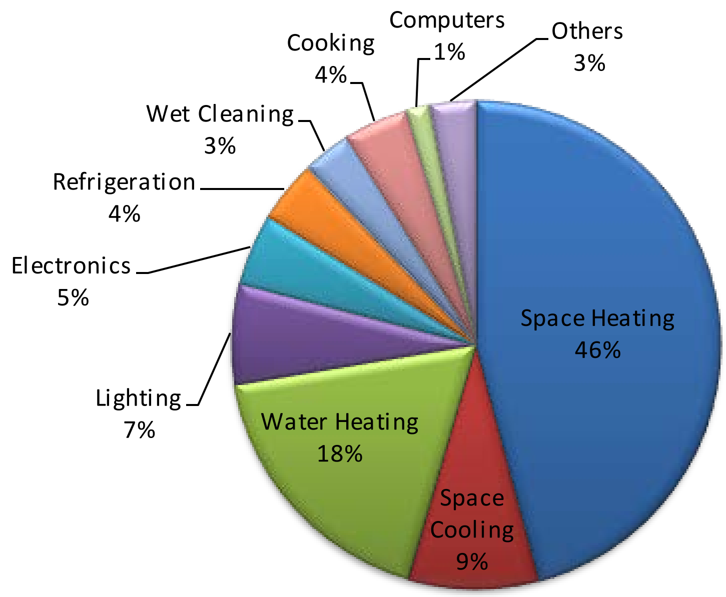

Figure 2.1. 2008 Residential Energy End-Use Splits, by Fuel Type. EERE Buildings Energy Data Book, (U.S. D.O.E. 2011).

There have been houses built that utilized the sun's free energy through design features and vintage solar technology. The Carlisle house was designed in 1981 by Solar Design Associates in conjunction with the Massachusetts Institute of Technology and the U.S. Department of Energy. The Carlisle house was recognized as the first house with a roof integrated PV system in the United States (National Renewable Energy Laboratory, 2003). The Carlisle house had a 7.4kW PV array that cost $75,000 alone, installation not included. Some of the research that was done with the Carlisle house included net-metering and monitoring the livability of a solar-powered house. Before any research was done, the designers made it clear that photovoltaic technology was not affordable at that time. One of the major findings from this research was that the Carlisle house scarcely used 25 percent of the total electricity produced by the 7.4kW array. The rest of the unused electricity was sold back to the power utility (Stepler, 1981).

Over time, the net-zero energy approach to construction hardly became popular due to high cost of technology and initial costs to install, as well as homeowner uncertainty to alternative electricity production. The cost of electricity was another factor that affected whether or not photovoltaic power was affordable. Of course, electricity prices have always been widespread throughout the country and the differences in electricity pricing are a determining factor in deciding whether to build environmentally conscientious or not.

Fortunately there is hope. Figure 2.2 shows promise for the growth of the solar PV industry. It is also evident that the sun will provide the Earth with enough clean energy to power humanity for multiple generations to come, another 4.5 billion years approximately. It is now that humanity must act to save future generations by investing in renewable energies and start producing energy on-site (Schoder, 2011). Photovoltaic technology is predicted to be in almost 12 percent of single-family homes by 2035 as seen in Figure 2.2 (U.S. EIA, 2010).

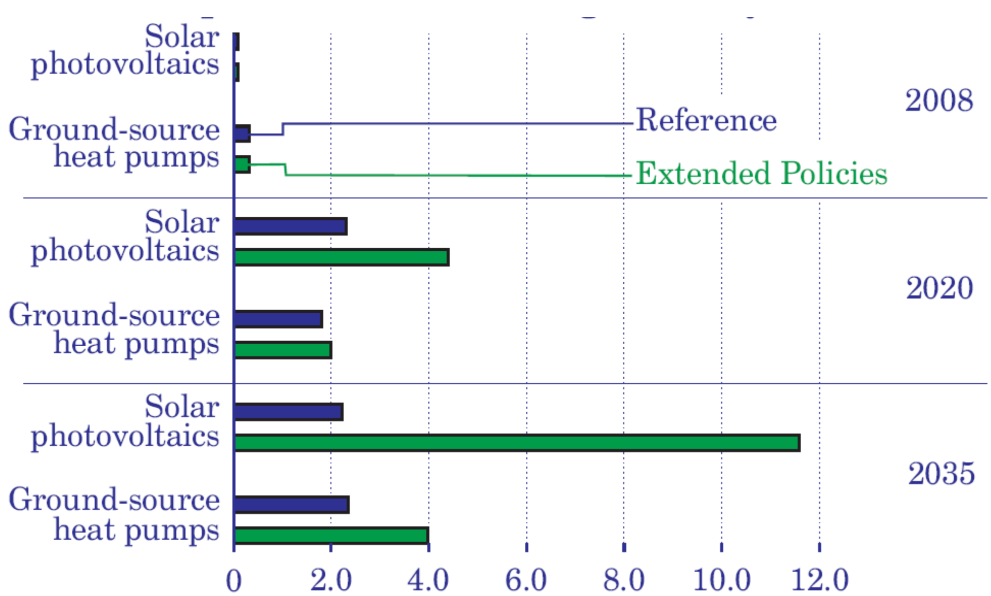

Figure 2.2. Predicted growth of solar photovoltaics through 2035 in single-family residences. Photovoltaic growth is compared with the growth of ground source heat pumps as a percentage of market share. (U.S. EIA, 2010).

2.3. Currently Available Sources

As stated earlier, there are numerous case studies and examples of energy-efficient, solar-powered homes all over the United States. Many of these studies of the built environment were funded through the U.S. Department of Energy's Building America partnership. In fact, 25,000 houses in 34 states were some way or the other were funded through the program and built as high performing, long-lasting, comfortable, and energy-efficient. A strategy of the Building America program was to develop an engineering systems approach to the development of new housing construction (Building America, 2010). This program publicized climate-specific case studies of energy-efficient houses built nationwide. These publications can be accessed for free on the website *www1.eere.energy.gov* (U.S. Department of Energy: Energy Efficiency & Renewable Energy, 2010).

One example of the Building America Program is the Carbury house, a 2500 square foot house built in a suburb outside of Houston, Texas. Designers from the Consortium for Advanced Residential Buildings (CARB) outfitted the Carbury with double pane vinyl windows and a new 3 ton A/C system. The HVAC duct inside the Carbury was installed in conditioned space to save on energy losses. For comparison, an identical control house was built to mimic the Carbury. However, this house had single pane windows, a 5 ton A/C unit, and ductwork in un-conditioned space. By doing a simple descriptive comparison between the two houses, the Carbury saved an average of $362/year when compared with the control home (Griffiths & Zoeller, 2001).

Another firm that has extensive research with solar-living homes is Steven Winter Associates (SWA). SWA has built many trial homes with advanced building technologies such as photovoltaics, tight envelope construction, and passive window strategies. The Wisdom Way Solar Village in Massachusetts incorporated these things and is a living example of how a typical subdivision can be near net-zero energy (Steven Winter Associates, 2009).

More than a third of the energy consumed in U.S. residences goes to heating, cooling, and appliances (Little, 2005). “It is critical to monitor and understand how electricity is being consumed inside typical homes (pg. 35).” That is what Jeff Christian, director of Buildings Technology Center at DOE’s Oak Ridge National Laboratory, is trying to do. He states, “Let’s make it a grand challenge to make solar homes affordable enough on the front end to become the norm in U.S. neighborhoods, rather than the exception (pg. 35).”

Mr. Christian built four, 1,100 square feet, three bedroom homes in Lenoir City, Tennessee. These houses were affordable, net-zero homes built by Habitat for Humanity costing a mere $100,000 each. “By making these houses Volkswagen’s instead of custom-built Cadillac’s, a solar powered house can be affordable (pg. 36),” said Christian. The four houses were built with structurally insulated panels (SIPS), a light colored roof, mechanical ventilation, and overhangs on the windows. The houses also included passive design, as 70 percent of the windows faced the south. Each house was outfitted with a geothermal heat pump sized for the Tennessee climate. Mr. Christian also continues to monitor appliance, lighting, HVAC, and comfort levels within all four houses (Little, 2005).

One of the most recent columns in the ASHRAE journal focused on a 2007 Solar Decathlon house which addressed economic and energy-efficient residential building topics (Newell & Newell, 2010). The Equinox was the University of Illinois’ entry for the 2007 competition. The authors, Ty and Ben Newell were heavily involved with the very successful Equinox house. In turn, they have written many informative inserts ranging from topics such as the thermal mass of a house, sealing a house, and effects of heat transfer through the ground (Newell & Newell, 2011). One article, in particular, was an article discussing windows & overhangs. For a Central Illinois climate, they concluded that, “the cost of a window outweighs the potential savings due to improved energy performance (pg. 137)." It is possible to over-construct a building, reaching a point of diminishing returns. The article goes on to state that, for houses similar to the Equinox house, the window-to-wall area ratio should be around 10 percent (Newell & Newell, 2010). After looking at the Equinox photographs in the article, the INhome was found to be strikingly similar. Surprisingly, there was no design inspiration modeled with the Equinox House in mind when the INhome design was conceived.

All of the engineering systems inside a net-zero house must be integrated to work with each other in order to optimize energy consumption for a given climate. The 2011 Solar Decathlon was the perfect research platform to test the engineering systems performance of the Purdue INhome, which was specifically built to meet the demands of the Midwest climate.

2.4. Solar Decathlon

The U.S. Department of Energy has held the Solar Decathlon on the National Mall in Washington D.C. since 2002. The inaugural Solar Decathlon attracted over 100,000 visitors to 14 solar-powered houses in just one week (Walker, 2003). From the beginning, a key goal of the U.S. Department of Energy was to reduce the amount of energy consumed by the residential sector by 2020. Therefore, the Solar Decathlon has been held in a heavily visited location in hopes of advertising solar-living to the public.

The Solar Decathlon is a two year student-led project where 20 collegiate teams design, build, test, and showcase solar-powered houses to the world. In total there have been four past competitions, 2002, 2005, 2007, and 2009. Past teams have come from all over the world to compete in this prestigious competition. Solar Decathlon 2009 international had teams from Spain, Canada, Puerto Rico, and Germany. The 2011 competition had teams from New Zealand, China, Belgium, and Canada.

One of the many houses that did particularly well was the University of Illinois's Gable Home. In 2009, the Gable Home finished second overall and second in the Net-Metering Contest because the team optimized energy consumption inside the house first, and then maximized energy production second. A 9kW photovoltaic array helped the Gable home reach net-zero during the nine day competition. A LabVIEW data acquisition control platform was used to precisely and intelligently control the whole house (Dhople, Ehlman, Murray, Cady, Chapman, 2010).

One of the goals of the Solar Decathlon is to bring down the price of installing residential photovoltaic systems over the course of all Solar Decathlons. In 2005, Lew Pratsch, Project Manager for the DOE's Zero Energy Homes project stated that, "Within the next decade, zero-energy homes could cost no more than comparable conventional homes (pg. 35)" (Little, 2005). In the 2009 competition, only one house had a construction cost of under $250,000, which posed a threat to this goal (U.S. D.O.E., 2010). Unfortunately, with no constraints on how much a team could spend on the house, many photovoltaic systems were larger than necessary. There was a high correlation between the size of PV system and the final scoring for each house. For instance, in 2002 the average PV size was 5.2 kW. In 2009, it was 9kW and the winning team had a 17.8 kW array (Brearley, D. 2010).

The past four competitions had no limit on the value of each home. Several past houses reached the million dollar mark, a price tag the average American can't afford. Consequently, the 2011 Solar Decathlon was the first competition to have an affordability contest. The Affordability Contest required each home to be valued under an estimated builder's cost of $250,000. This was crucial to the way each team strategically planned for the competition. Valuable competition points were deducted if the team surpassed an estimate of $250,000 (U.S. D.O.E., 2010). The 2011 Solar Decathlon had only two teams estimated below the $250,000 mark. However, several other teams came very close to earning full points. Final scoring is discussed later in Chapter 4.

On the other hand, many teams opted to push the innovation design envelope and overlook the Affordability Contest, as the Solar Decathlon has historically displayed in past showcases. A valid perspective of how the Affordability Contest affected the 2011 Solar Decathlon competition was presented in the November 2011 issue of ARCHITECT, the magazine of the American Institute of Architects.

Grimes & Mays (2011), wrote the following:

> The students at this year's Solar Decathlon tackled a new challenge as part of the biennial competition: Designing their energy-efficient houses for $250,000 or less. Solutions included some pointedly avant-garde designs. Yet some students and faculty advisers worry that the Decathlon's new emphasis on affordability will deter innovation and lead to the construction of more-pedestrian homes. Other participants found fault with the system for estimating costs. Nevertheless, a few entries succeeded in making a significant point: going green can have a mass-market appeal. (p. 70).

By assessing final scoring from competition contests, the author was able to determine which engineering systems inside the houses were successful and affordable. The mechanical, water heating, and appliance systems that prevailed throughout the competition will be discussed in this research. These systems had to consume minimal amounts of energy, while performing flawlessly in order for each house to become net-zero. A powerful way of influencing photovoltaic housing was having each team reach net-zero energy status at the end of the competition.

The Energy Balance Contest determined if each house was net-zero over the nine day contest period. In other words, were the houses able to produce as much electricity as consumed with photovoltaic electricity generation throughout the contest week? In Figure 2.3 the 2009 teams that were above 0 kWh at the end of the week were net-positive, generating more electricity than their house consumed.

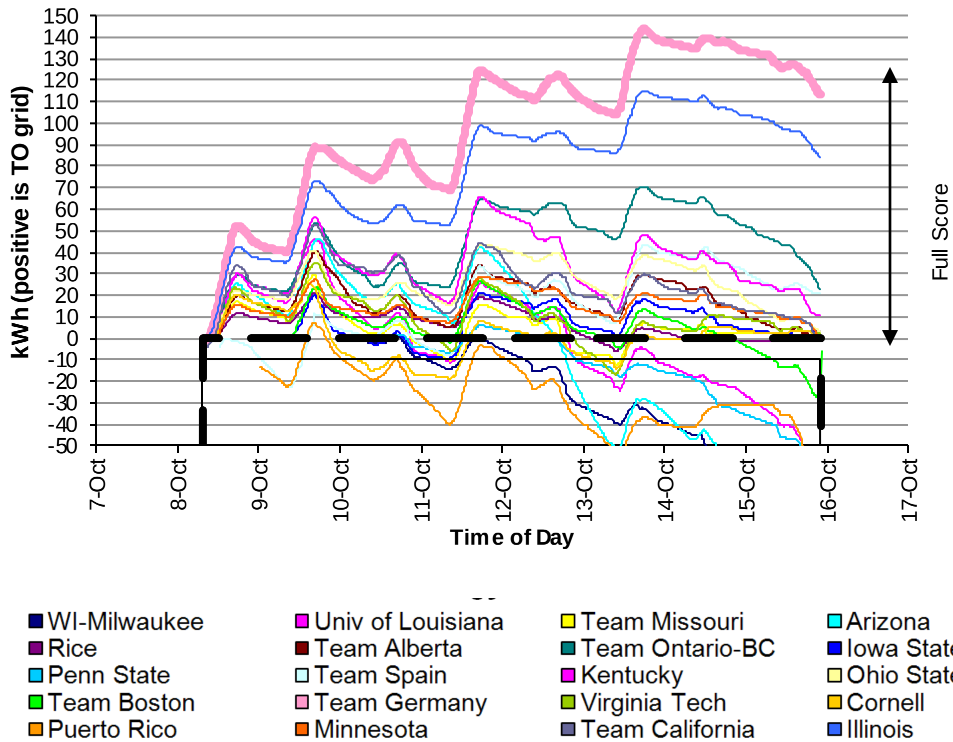

Figure 2.3. Instantaneous energy balance of each 2009 Solar Decathlon home trended throughout the nine day competition. (U.S. D.O.E., 2009).

By looking at Figure 2.3 it is clear that Team Germany produced an additional 110kWh in order to win first place in the Energy Balance contest. Unlike the 2011 competition, 2009 teams earned more points by having bigger photovoltaic arrays. This enabled more teams to become net-zero, but greatly distorted the general public's outlook on the cost of solar living. Ideally, the teams that were just above the dashed black line in figure 2.3 would have designed the most affordable and practically sized array. The 2011 competition was the first competition to bring the cost of photovoltaic technology into reality for the everyday homeowner. The final outcome of the Energy Balance Contest enabled the author to identify which PV systems were adequate, not over-sized, and cost-effective.

A lasting benefit to building a research house is the ability to monitor it for future data collection and research. This was exactly what residential energy efficiency researchers at Missouri University of Science and Technology have done. With data from all monitoring devices in three net-zero energy homes, comparisons have been made of the houses performance. Two main principles were identified; energy generated per house and energy consumed per house. One of the final goals of Missouri University S&T was to develop a cost effective home automation and energy management control system, ultimately continuing efforts to reduce energy consumption in the residential sector (Wright, Baur, Grantham, Stone, & Grasman, 2010).

The transitioning of technology and solar-living in general has been visible as the Solar Decathlon has progressed through time. New improvements to past themes and innovations that scored well in the 2011 Solar Decathlon were recognized in this research. The 357,000 visitors to the 2011 competition were inspired by the affordable and breathtaking designs. The Solar Decathlon, now entering a second decade of showcasing solar powered houses, is properly and effectively influencing solar living to homeowners not only in the United States, but worldwide.

2.5. Summary

It is evident that several excellent examples of building net-zero, energy efficient homes exist already. Past examples from sources such as the Building America Program, NREL, NAHB, and the Solar Decathlon have provided outstanding models to build from. However, as technology progresses more advanced ways to build energy-efficiently are discovered. It is through continued research and discovery that these building techniques will continue to expand.

CHAPTER 3. STATEMENT OF WORK AND METHODOLOGY

The author had a leading role in transforming the INhome from an idea to final product. Valuable lessons learned and design steps taken throughout the two year project will be discussed in attempt to bring more awareness towards building net-zero energy housing. Net-zero energy homes have traditionally been expensive to build and developing a valid, stand-alone research experiment was not practical for a Master's Thesis. Fortunately, the Solar Decathlon represented a grand opportunity where 20 individually unique teams competed in the same identical contests and were judged without bias or external interests.

3.1. Three Step Design Process

From day one, the Purdue INhome team was committed to being a strong competitor during the 2011 Solar Decathlon. To ensure success during the competition and ultimately reach net-zero, the team employed a three step design process illustrated in Figure 3.1. The team set out to properly orient and design the building envelope first. Secondly, the team minimized unwanted energy consumption wherever possible. And lastly, the team maximized energy production through a properly sized photovoltaic array.

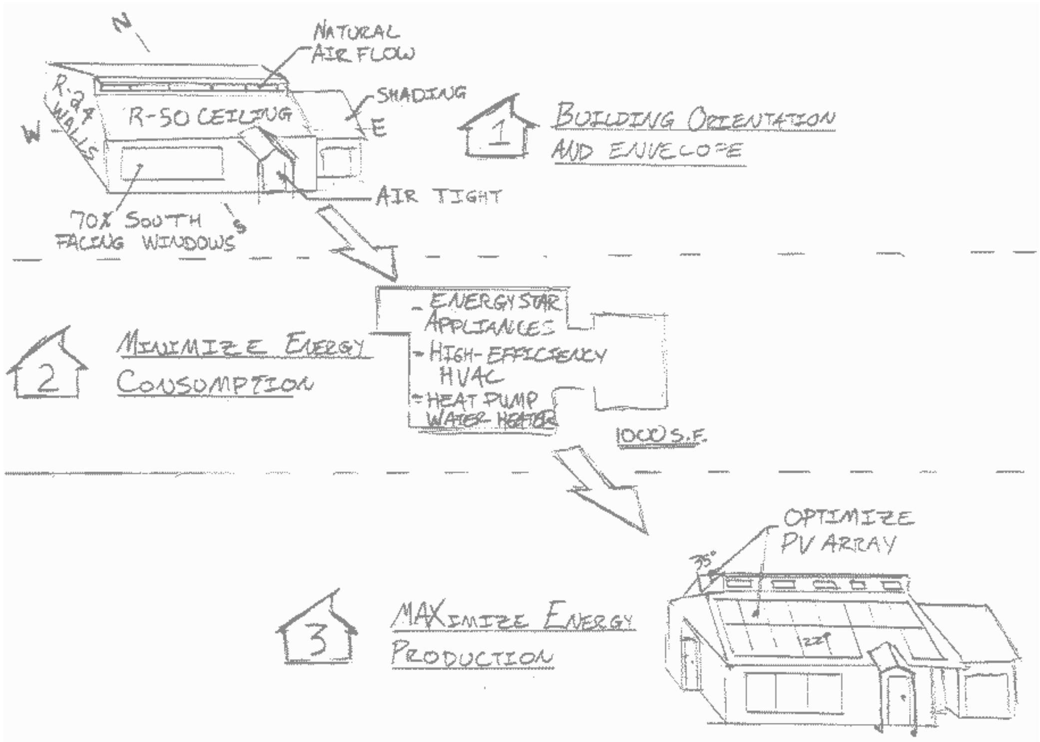

Figure 3.1. Three step design process to reach net-zero.

3.1.1. Step One – Building Envelope

The INhome utilized several passive design features as illustrated in step one of Figure 3.1. Mitigating any undesired energy usage in a high-profile solar living competition was essential. From the inception of the INhome design, the team wanted the house to be effectively insulated, sealed air tight, adequately lighted, and properly ventilated. By following these several design goals, the INhome had a strong foundation to begin with.

Proper orientation is the first key to having a successful solar powered house. The INhome was oriented to have large southern facing windows that allow sunlight to enter the living room. To be exact, the windows on the south side of the house made up 73 percent of all windows. Furthermore, overhangs provided shade over all south-facing windows. This prohibits sunlight from directly hitting the windows during the summer, yet during the winter allows sunlight to be absorbed. Indirect daylight will still be able to enter the building, minimizing the need for artificial lighting. The shading of windows and exterior walls throughout the year is very important, so beneficial that ASHRAE Standard 189.1-2009 requires all above grade East and West walls to be partially shaded. This is a low-cost and effective way of minimizing unwanted heat transfer through a building (ASHRAE, 2009).

Heat transfer through a building's envelope is partially determined by the type and amount of insulation. Fortunately, there was a product on the market that enhanced the INhome's structure in many different ways. Structural insulated panel systems (SIPS) provided excellent insulation values and protection against thermal bridging. Moreover, the SIPS were pre-manufactured in a factory and then assembled on-site in just two days. This also greatly reduced the amount of on-site construction waste. The INhome was designed to have true, four inch (R-24) walls and eight inch (R-50) ceilings, while all at the same time being easily disassembled. In fact, the INhome was disassembled three times and assembled four times throughout the entire project. Figure 3.2 is an image of the practice disassembly Team Purdue conducted in preparation for the real event.

Figure 3.2. Disassembly of the INhome.

SIPS panels also provided superior protection against air infiltration, which affects rate of heat transfer. A typical house cannot control air infiltration, causing the mechanical systems within a house to operate with uncertainty, more often running than idling. With the help of low-energy mechanical ventilation, an air-tight house can decrease HVAC runtime and also provide healthier indoor air.

Throughout the duration of the project, an energy model of the INhome helped determine and ensure that energy consumption associated with each design change was appropriate. An example was determining the proper overhang distance on all south facing windows. This type of pre-construction planning was crucial to design a structure so influenced by energy flow. The INhome team used Energy Plus to model the structure, a free software package available from the United States Department of Energy.

3.1.2. Step Two – Minimize Energy Loads

Step two of the design process minimized energy loads inside the house. An overall team goal was to make the INhome as comfortable as possible, therefore all common household amenities were included in the design such as a family-sized refrigerator and oven. Figure 3.3 is a breakdown of the budgeted energy usage for the INhome during the 2011 Solar Decathlon. From great amounts of energy consumed by water heating to the amount of energy an additional 13 watt CFL light bulb consumed, electricity inside the INhome was carefully considered to ensure a net-zero energy design. To provide the best overall value, the team also had to balance energy consumption with affordability and aesthetics.

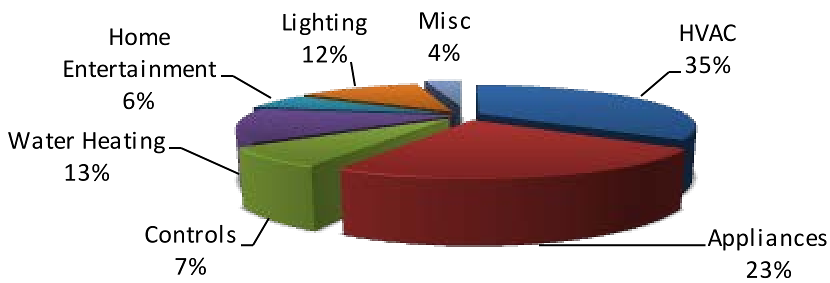

Figure 3.3. Budgeted end-use energy consumption of the INhome.

Appliances in the INhome were not the most expensive, top-of-the-line appliances. A few of the appliances were smart appliance capable (clothes washer/dryer and water heater), which highlighted the future of appliances. However, the overarching appliance vantage point was making sure the appliances were Energy STAR® rated and could be affordably purchased at any local home improvement store.

The INhome used a heat pump hot water unit to provide hot water throughout the house. This innovative unit consumed less than half the energy as a typical 50 gallon electric water heater. Furthermore, at the time of the competition, heat pump water heaters cost around $1,200. If a heat pump water heater replaced an older electric water heater, the payback period would typically be within 2-5 years.

Heating and cooling of the INhome was made possible by using an ultra-efficient air-to-air heat pump unit. The outdoor unit had two compressors, a smaller compressor for low heating and cooling loads, and a larger compressor for heavier loads. This unit was integrated with the indoor air handling unit, which had a variable speed fan. Ductwork was then distributed throughout the house to ensure proper air distribution. This system was connected together via a state-of-the-art, modern day thermostat. Energy savings were realized using appropriate scheduling, adjustable humidity and temperature set points, live energy monitoring, and wireless capabilities.

In general, most systems of the INhome were not extravagant and complex assemblies of several different components, but simple off-the-shelf products that were currently available on the market. Designing the INhome using this equipment eliminated any uncertainties in performance, reliability, and cost. This way of minimizing energy loads within a house can effectively be carried over to current residential construction today.

3.1.3. Step Three – Optimize Energy Production

The last step optimized the photovoltaic array size to ensure the INhome would be net-zero during the competition, yet be as affordable as possible. To do so, each energy load inside the house that had an associated contest was investigated. A spreadsheet was developed to determine the overall required energy throughout the competition. For example, the INhome had to turn on 800 watts of lighting for several hours each night. This exact amount of energy was calculated using this spreadsheet.

The spreadsheet, found in Appendix A, calculated amount of energy required and computed an array size based off several different factors. One of the most dominant factors was the amount of sunshine available during the competition time frame. Photovoltaic module efficiency, wire loss, and tilt angle efficiency were valuable factors as well. Fortunately for Team Purdue, West Lafayette, IN and Washington D.C. are similar in geographical latitude. Therefore, no adjustments in tilt angle were necessary for the competition. In the end, the selected array was 8.64kW in size and had an overall system efficiency of 80 percent. The INhome's installed photovoltaic array is shown in Figure 3.4. A key feature of the INhome was the angle that the modules were installed at. The south-side modules were installed at 22° and 35° for the north-side array.

Figure 3.4. The INhome's installed photovoltaic array.

3.1.4. Construction and Commissioning

Student team members built and tested the INhome on Purdue's campus during the summer of 2011. The final house is visible in Figure 3.5. This work was critical in making sure all the system's inside the INhome were installed and functioning as intended. All testing procedures conducted were done to properly commission the INhome. All commissioning procedures were documented. Developing these testing procedures was necessary for the INhome to be disassembled, transported to Washington, D.C., and assembled in seven days.

Figure 3.5. The Purdue INhome.

3.2. Methodology

This project focused on the engineering performance of an affordable, net-zero energy house using both quantitative and qualitative methodologies. Several quantitative experiments had the greatest effect on the outcome of the engineering performance of the house. In addition, a qualitative review of the engineering merit of each house was performed. A mixed methods research protocol was the best way to give a thorough explanation of what engineering systems performed best inside an affordable, net-zero energy home.

3.3. Research Platform

The 2011 Solar Decathlon provided an excellent framework to gather information over current net-zero energy housing. In all, 19 university-led teams competed in the competition (Team Hawaii withdrew from the competition early-2011). The competition was held from September 23 through October 1 in the year 2011 on the West Potomac National Mall in Washington, DC. This 10 day period was when all contests were completed. The competition officials released all scoring documentation for each house at the conclusion of the Solar Decathlon in October 2011. Both quantitative and qualitative contest results were made publicly available through the DOE's Solar Decathlon website.

3.4. Data Collection

Out of the 10 contests, six were critical to this research project. The most important contests were the Comfort Zone, Hot Water, Energy Balance, and Affordability Contests. As quantitative measures, all contests were used to statistically measure and compare each house to the INhome. The Engineering Contest, a purely qualitative method detailed the engineering jury's critique and score of each house. This contest showcased similarities amongst successful teams.

Each house was subject to identical contests and reviews in order to provide unbiased data collection and engineering evaluation. Quantitative data was recorded identically amongst all houses as a performance metric. The qualitative research data collected by the Engineering contest was judged by a jury of three professional engineers with abundant industry experience. The results of these qualitative and quantitative contests depicted what common patterns existed between each house and ultimately provided an affordable net-zero energy home. The researcher determined if any strong correlations were apparent between contest outcomes and all influential variables.

3.4.1. Additional Sources

The researcher also had access to all other contests of the Solar Decathlon. During the actual public showing of all 19 houses, the researcher was able to tour each house and gather an in depth review of each house. Specific attention to detail was given to each house’s Engineering merit and photovoltaic system.

3.5. Credibility

Having 19 net-zero energy homes valued near $250,000 each was a great sample size for this research. The researcher was able to freely collect information that was unbiased and unaltered. The Solar Decathlon organizers did an impressive job setting up the competition to have each house judged and measured at equal thresholds throughout the week.

3.5.1. Credibility of Researcher

The researcher was a key member of the Purdue INhome Solar Decathlon team for the duration of the two-year project. The researcher was the

Engineering Manager for the INhome during the entire two year project. Responsibilities of the researcher included working with other valuable students to design, install, and test photovoltaic, mechanical, electrical, plumbing, control, fire protection, and other miscellaneous systems inside the INhome.

3.6. Summary

In summary, key design steps for building the Purdue INhome, a net-zero energy house, were to optimize the building envelope first, minimize energy consumption next, and then finally optimize the photovoltaic array. The Solar Decathlon provided a great framework to collect data and verify whether or not this design approach was successful. Moreover, an evaluation of all Solar Decathlon houses will be done using the contests most relevant to this research.

CHAPTER 4. RESULTS

The 2011 Solar Decathlon featured the 10 distinct contests summarized in Table 4.1. The five contests in the left column were quantitative, using measured data. The five contests in the right column were subjective, relying on the input from a jury. The contests that were critical in developing definitive arguments in this research are highlighted. The results from each of these important contests (highlighted) will be discussed in this results section.

Table 4.1.

Significant 2011 Solar Decathlon Contests.

Measured Contests	**Juried Contests**
Appliances	Engineering
Hot Water	Affordability
Comfort Zone	Market Appeal
Energy Balance	Communications
Home Entertainment	Architecture

4.1. <u>Competition Data</u>

All 19 solar powered houses were measured on an unbiased platform for all 10 contests. Data from the measured contests was recorded every fifteen minutes for a total data collection of 194 hours. Normalized data regarding the performance of each house was made possible with all houses being measured the same way. Live data and corresponding scoring was uploaded to a Solar Decathlon spreadsheet every fifteen minutes throughout the week. Having access to this live scoring enabled teams and the general public to gauge how each house was performing throughout the week.

4.1.1. Final Scoring

The University of Maryland's Watershed was the overall winner of the 2011 Solar Decathlon. Second and third place teams were Purdue University's INhome and the University of Victoria at Wellington's First Light. Win or lose, all teams that competed in the competition did a wonderful job of displaying their houses and the possibilities of solar living. Final scoring from each contest can be referred to in Appendix B. Appendix B gives overall scoring for each team in all 10 contests.

4.1.2. Weather

The autumn weather in Washington D.C. was very troubling for many teams. In fact, the weather was the primary independent variable that influenced quantitative contest results. Hot, humid, and cloudy weather proved too problematic for many teams. Figure 4.1 displays the outdoor temperature and relative humidity for the entire competition week. Notice that the outdoor relative humidity very seldom dropped below 60 percent, which was the maximum for indoor relative humidity levels. Furthermore, the outdoor temperature surpassed the 80°F mark almost every day.

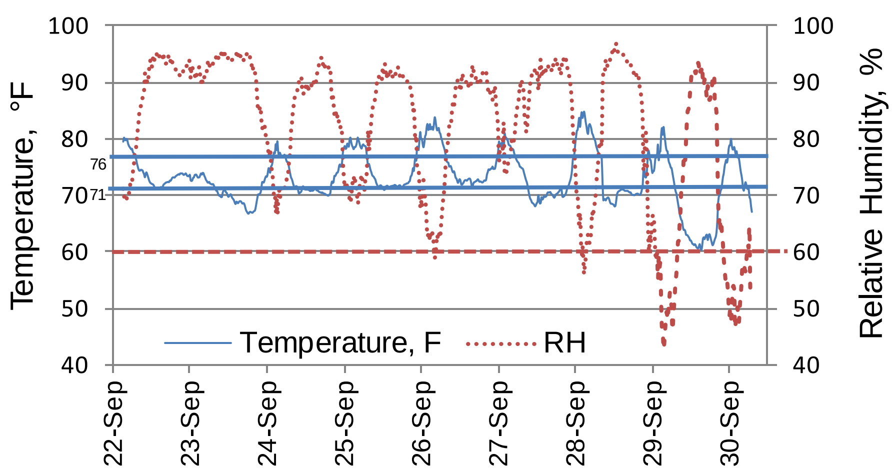

Figure 4.1. Outdoor temperature and relative humidity during the competition.

The lack of overall sunshine during the competition week added to the disappointing weather, especially when all houses benefited from sunshine in order to generate electricity. Figure 4.2 illustrates the global horizontal solar radiation that was available during the contests. Unfortunately, only four days reached over 500 W/m^2. In contrast, standard testing conditions for rating photovoltaic modules is set at 1000 W/m^2. In plain terms, the lack of sunshine limited the photovoltaic arrays to operate at seemingly half-capacity. Many teams had a hard time competing with poor weather and less-than-friendly amounts of sunshine.

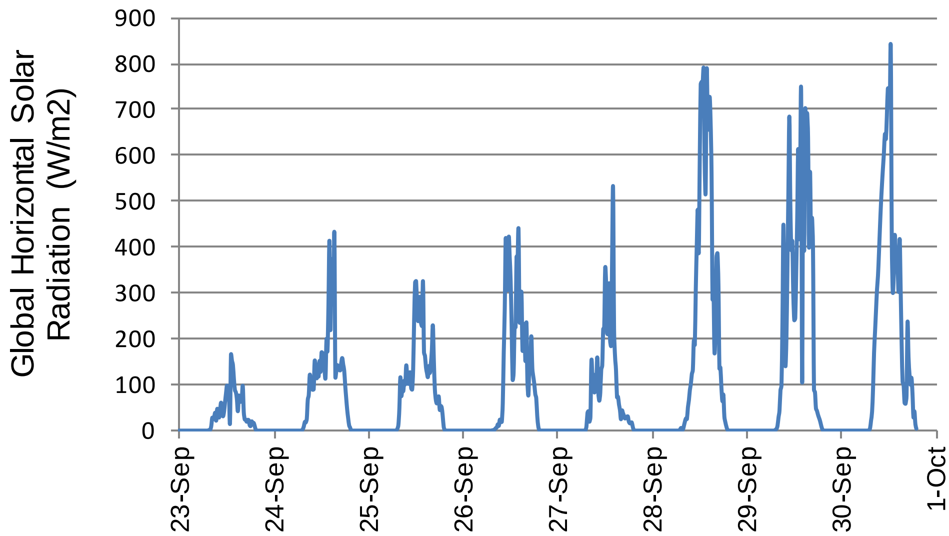

Figure 4.2. Sunshine available during the competition.

4.1.3. INhome Performance Monitoring

Specific energy consuming characteristics were particularly easy to record in the Purdue Solar Decathlon home. Energy usage was monitored in almost all circuits throughout the house via the main electrical panel. By monitoring energy usage, large electrical loads inside the INhome such as lighting, appliances, HVAC, and water heating were shown to save electricity during the competition.

These energy savings will be discussed during each contest breakdown. Furthermore, efforts to monitor energy consumption inside a typical house are particularly advantageous to discover how much each load is costing the homeowner. Appendix C explains in detail how the energy consumption inside the INhome was recorded.

4.2. Contest Breakdown

This research will discuss energy saving findings in four of the measured contests, as well as the juried Engineering and Affordability Contests. Major findings will be supported with unbiased contest data. Discussion of these findings will continue in the next chapter. Lastly, each of the following contests was worth 100 points each.

4.2.1. Engineering Contest

Functionality, efficiency, innovation, reliability, and documentation were the five different characteristics critiqued in the Engineering contest. Appendix D details how each team scored. Several teams took unique engineering design approaches, while others remained consistent to the competition requirements. In general, those teams that pushed the envelope with new innovations typically scored better in the Engineering contest. Team Purdue's detailed Engineering scorecard can be seen in Appendix E.

The innovation category evaluated each design based on the following two questions; "Were any unique approaches used to solve design challenges?" and "Do the proposed innovations have true market potential? There was a high correlation of the top Engineering scoring teams with respect to their innovation scores. In fact, three out of four teams earning full innovation points finished in first, second, and fourth place in the Engineering contest.

Another interesting discovery made from the Engineering contest is that the top two overall teams scored best in the documentation sub contest. Therefore, the importance of professionally developing construction documents and material for each house was confirmed. The houses that were assembled and presented with a high level of professionalism tended to perform and score better overall.

Teams that scored well in the Engineering Contest also had a better chance of becoming net-zero as well. Of the top six teams in the Engineering contest, five reached net-zero during the competition. It should be noted that only seven teams reached net-zero.

4.2.2. Affordability Contest

The Affordability Contest required each house to be professionally estimated at or below a value of $250,000. By limiting the cost of each house, solar living became more recognizable by the general public. This contest ultimately challenged each team to select the most cost effective components in each house.

There were only two houses that were estimated to be under the $250,000 set point as seen in Appendix B. All houses were subjectively estimated with respect to team specifications. Installation and contingency factors were included with the estimate as well. There were nearly 150 line items estimated per house, ranging from windows to solar modules. Lastly, the average cost of all houses was $318,000 with values ranging from $230,000 up to $470,000.

The INhome was estimated at $257,000. A line-by-line breakdown of the INhome’s cost estimate is in Appendix F. Of all line items the most expensive was the photovoltaic system, which was valued at nearly $56,000. However, this was typical of all homes. In general, the INhome featured high efficiency, off-the-shelf products that helped keep overall costs low.

Fortunately, affordable solar living already exists in some locations of the country. As the price of electricity continues to increase, affordable net-zero energy housing will become more and more affordable to the average homeowner. This contest has definitely helped shape the future of solar living.

4.2.3. Comfort Zone Contest

The contest that visibly set teams apart was the Comfort Zone contest. In two ways, the end result of this contest revealed the most affordable and best-performing HVAC systems. The Affordability Contest revealed the cost of each system while the Comfort Zone Contest revealed top performers. Many HVAC systems were put to the test, as several teams could not keep pace with Mother Nature and missed out on valuable points.

Contest rules required that each house be within specific temperature and relative humidity set points. The temperature in each house had to be between 71°F-76°F to earn full points. Furthermore, the indoor relative humidity inside each house had to be below 60 percent for full points. Temperature and relative humidity sensors were placed on microphone stands throughout each house to ensure that indoor comfort levels were uniformly distributed. Most houses had two to three microphone stands that were wired directly into the competition data logger. Values for the contest were typically measured from 3PM, after public tours, through 9AM the next morning.

The weather proved to be a bigger problem than expected for many teams. Hot and humid weather challenged all teams to dehumidify properly without over-cooling. Solar Decathlon Founder and Director, Richard King described the challenges all teams faced during the contest week in this SOLAR Today article.

Richard King (2012) wrote:

> For competing teams, impressing the juries was only half the story. Their houses also had to perform. One of the demanding tasks during this year's competition ended up being dehumidification. The weather in Washington was rainy and cloudy, resulting in very humid conditions. The relative humidity outside never fell below 90 percent for the first six days (with temperatures hovering around 80°F, or 27°C), yet teams had to keep indoor humidity below 60 percent to score points. Try doing that when you have to open your house to thousands of visitors each day, sometimes in the rain. (p.25).

Many teams designed their HVAC systems using mini-split systems set up in a ductless or ducted layout. In fact, 14 out of 19 houses utilized them. These mini-split systems had an outdoor condensing unit that was connected to an indoor air handler. The indoor air handler was either mounted on a wall that directly cooled and dehumidified a room, or it was connected to ductwork that typically served one or two zones. Mini-splits have traditionally been used in smaller buildings were running ductwork is problematic. Hence, the popularity of this type of system in Solar Decathlon designs. Other teams utilized radiant heating and cooling, absorption cooling, a traditional forced air unit, and an air conditioner integrated with an energy recovery ventilator (ERV).

The temperature points of the contest were worth 75/100 points. Many teams were able to earn a majority of these points throughout the competition. Figure 4.3 illustrates similar temperature scoring amongst different designs from New Zealand, Tennessee, and Purdue. New Zealand and Tennessee both utilized a ducted mini-split, while Purdue used a traditional forced air system.

There is no distinct variance as all three teams were able to keep within the temperature set points for a majority of the competition.

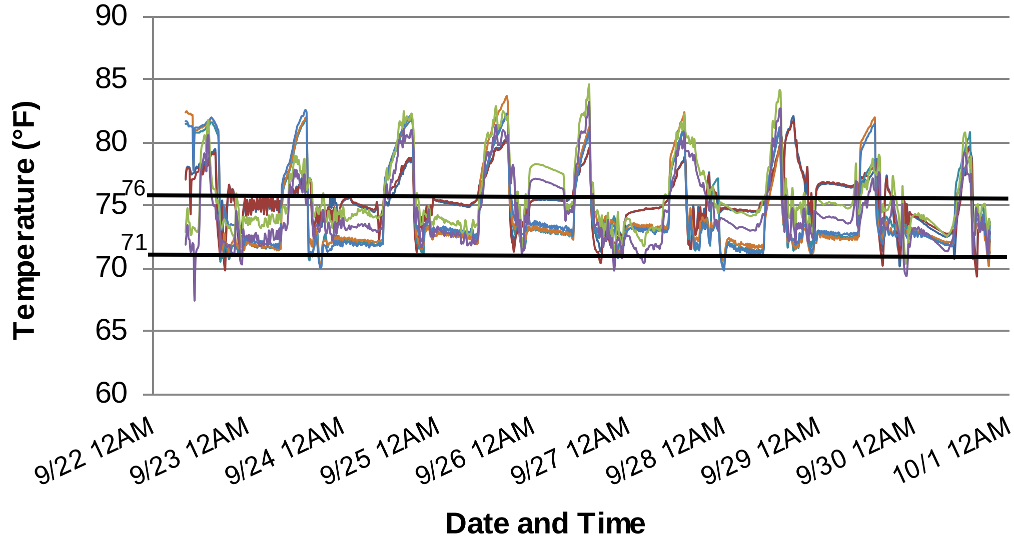

Figure 4.3. Indoor temperatures during the competition.

Dehumidification amongst houses had a different outcome. Figure 4.4 details the inconsistencies in relative humidity spread when compared to the temperatures shown in Figure 4.3. New Zealand and Tennessee are the upper two dashed lines, while team Purdue is the lower line shown as solid. This graph is a sample that illustrates the dehumidification efforts amongst several teams.

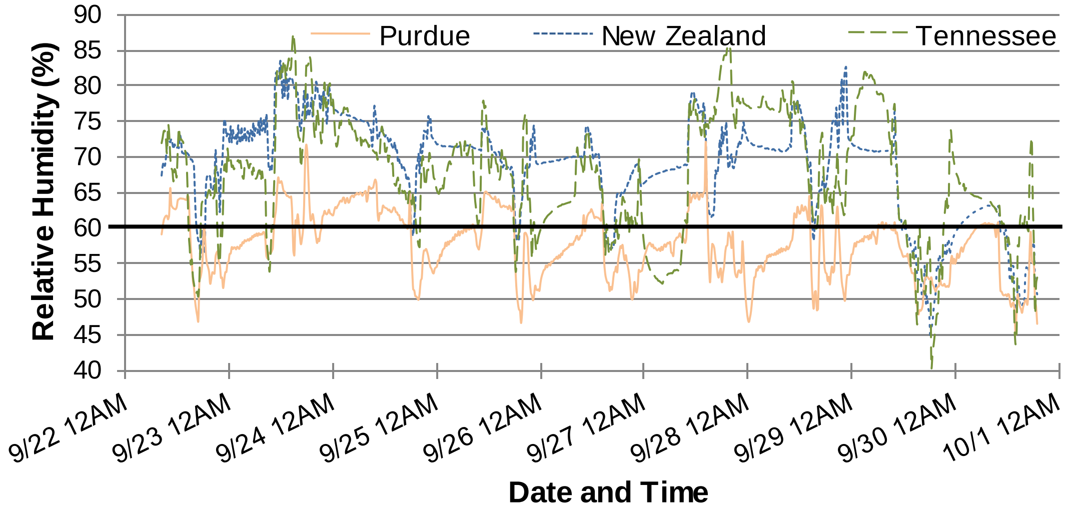

Figure 4.4. Indoor relative humidity during the competition.

Teams that were able to dehumidify and keep zones within the right temperatures prevailed. Ohio State, Purdue, and Maryland respectively finished atop the competition. The HVAC systems inside of these homes were very different from each other.

Ohio State utilized an elaborate mini-split heat pump unit integrated with a refrigerant to water heat exchanger. Hot water used to condition the air was mainly generated via two solar thermal collectors. The team also utilized solar thermal hot air collectors, a desiccant dehumidification wheel, energy recovery ventilator, and a phase change material to pre-condition air entering the air handling unit. Although this system was very complex and specialized, the Ohio State HVAC system won first place in the Comfort Zone Contest.

Team Purdue utilized an off-the-shelf HVAC system that performed very well. The team used a two stage heat pump connected to a variable speed air handling unit. Similar to the other two houses, ductwork was run throughout the house to ensure proper air distribution. The HVAC system stood out because of its ability to constantly dehumidify at low fan speeds without over cooling the air temperature.

Maryland utilized a very innovative dehumidification system with a mini split heat pump. Solar thermal collectors worked in conjunction with a liquid desiccant dehumidification cycle. A two stage lithium chloride brine solution was used to pull unwanted humidity out of the indoor air. This system worked very well in the Washington D.C. weather.

However, a large difference between the teams was the cost of each HVAC system. Figure 4.5 illustrates the final scoring and cost of each HVAC system. Notice that the dark square and triangle on the graph performed very well, but had an estimated mechanical system cost of over $20,000. Team Purdue, marked as the blue dot, was estimated under $10,000, while finishing second in the Comfort Zone Contest.

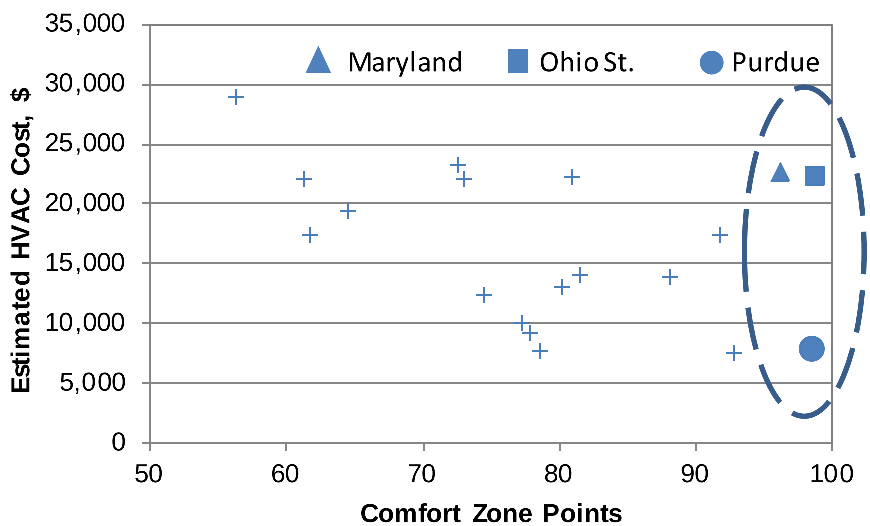

Figure 4.5. Mechanical Cost and Comfort Zone Results.

The additional dehumidification equipment used by many teams scored well, but also increased cost. The mechanical equipment used by Team Purdue performed great and was also the most affordable system. Furthermore, the Purdue INhome had to remove additional latent moisture that came from the Biowall, an indoor plant wall integrated with the HVAC return.

4.2.4. Hot Water Contest

The second contest that separated teams was the Hot Water contest, which required each team to draw on average 40 gallons of hot water per day. In total, there were 16 hot water draws in all that teams could earn up to 100 points. This contest was set up to mimic typical water use for an average family of four in order to test hot water heaters. Therefore, the shower of each house was measured to deliver at least 15 gallons of 110°F water in less than ten minutes. Many teams scored well in this contest. Teams either used two types of hot water heaters; solar thermal systems or heat pump water heaters.

Solar thermal water heating is done by orienting a panel of solar collectors, typically in glass tube form, towards the sun. Sunlight is then absorbed throughout the day by the collectors and transferred into a liquid medium. This liquid is normally a mixture of water and glycol in closed loop form that continuously transfers heat from the collectors to a storage tank. Most solar thermal storage tanks are equipped with a 2kW or larger electric back-up heater. Depending on the size and complexity, solar thermal water heaters used in the Solar Decathlon ranged in price from $3,750 to $11,200. It should be noted that some solar thermal systems were integrated with mechanical systems. However, these integrations were increasingly costly in both affordability categories, water heating and mechanical.

Heat pump water heaters use a vapor compression cycle to capture energy from surrounding ambient air and then transfer that energy into water. The thermodynamic process behind a heat pump enables one input unit of electricity to be transferred into two output units of heat, or hot water. Therefore the 40-50 gallon heat pump water heaters use considerably less energy than a standard electric water heater, which typically has a one to one ratio of electricity input to hot water output. Typical heat pump water heaters found in the competition were estimated around $1,500.

With cloudy weather predominantly throughout the week, heat pump water heaters outperformed solar thermal systems. In fact, seven teams earned all 100 points and of those seven teams, five utilized heat pump water heaters. Furthermore, of the seven teams that reached net-zero, five teams used heat pump water heaters. And lastly, only six teams in all used heat pump water heaters. Heat pump water heaters are affordable, reliable, and a very wise choice when designing a net-zero house.

4.2.5. Appliances Contest

Each house utilized typical household appliances to compete in several contests, accounting for 86 total points overall. In general, these appliances that performed well at a reasonable cost dispelled the consumer myths that smaller, mini-appliances are better performing. The refrigerator, clothes washer and dryer, and dish washer all had specific contest requirements. Many teams used high-efficiency, off-the-shelf products to earn these points. The availability of these appliances is a very good step in reaching net-zero.

Specific contest requirements for all appliances were very well structured. The refrigerator had to be within (34°F) and (40°F) and the freezer had to be between (-20°F) and (5°F) to earn full points, up to 20 points overall. This contest was the only contest continuously measured for the duration of the competition. Therefore, refrigerators were the one of the largest consuming loads in most houses. The refrigerator inside the Purdue INhome consumed nearly 3kWh/day, which was nearly 12 percent of all energy consumed by the house.

All teams had to wash and dry a load of towels weighing around six pounds, eight times throughout the week. Teams could earn up to 60 overall points for successfully washing (20 points) and drying (40 points) the towels. Most teams earned all points by using standard-sized, high-efficiency clothes washer and dryer units. Some teams opted to air dry towels which proved problematic because the towels had to be returned to the original weight within two hours. Furthermore, most laundry loads were performed in the evening which restricted the use of sunlight for direct drying.

The last 20 points could be earned by reaching dishwasher water temperatures of at least 120°F. There were five dishwashing loads and 16 out of 19 teams earned all 20 points. Once again, standard-sized (18 or 24 inch), high-efficiency dishwashers were used in most houses.

4.2.6. Energy Balance Contest

Only seven of 19 teams produced more electricity than they consumed during the competition week, officially reaching net-zero. With the nine day competition week being particularly cloudy, a few teams properly minimized electrical loads and selected the best fitting photovoltaic array. Several common themes were found amongst the teams that reached net-zero and those teams that did not.

The Energy Balance contest measured energy produced and consumed by each house using current transformers. Each house was unique in its own energy consumption and production fashion. Figure 4.6 is a breakdown of final scoring for the Energy Balance contest. A positive energy balance (>0kWh) resembles houses that reached net-zero. On the other hand, a negative energy balance (<0kWh) resembles a failed attempt to reach net-zero.

The weather was the reason a majority of teams did not reach net-zero. However, several important factors or design steps not directly related to the weather had to be carefully considered to have a chance of becoming net-zero. The first of these is actual array size. Many teams carefully sized their array with respect to the internal loads of their house. Appendix A demonstrates Team Purdue’s breakdown of electric loads.

Teams that carefully sized their array and utilized conservative weather-safety factors reached net-zero. These seven teams had an average array size of 8.4kW and a cost of $48,700. The remaining twelve teams that did not reach net-zero had an average array size of 6.9kW and a cost of $31,250.

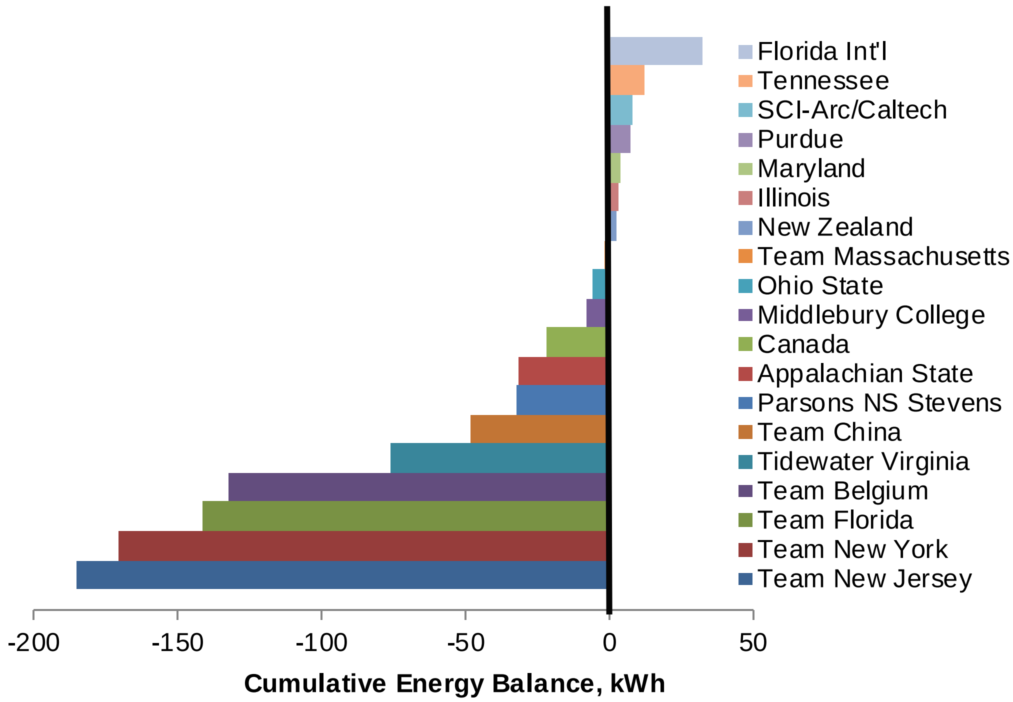

Figure 4.6. Final Energy Balance scoring.

Another design factor not related to the weather was the tilt angle at which the array was mounted at. All teams had to manage between architectural and engineering performance as an 18 foot height restriction limited the tilt angles of several homes. Table 4.1 lists a sample of different tilt angles that arrays were installed at. Notice that Appalachian State had an array installed at 0 degrees with respect to the horizon, limiting the ability of the panels to collect direct sunlight. However, a team such as New Zealand was able to purchase a smaller array and still reach net-zero by installing their array at 15°. In the end, tilt angle largely affected the energy performance of many teams.

Table 4.1.

Sample of Photovoltaic Installations

Team	**Manufacturer**	**Array Size, kW**	**Installed Cost, $**	**Tilt angle, °**	**Net-Zero?**
Purdue	SunPower	8.6	56,000	25*	Yes
New Zealand	Mitsubishi	6.3	28,500	15	Yes
Tennessee	Solyndra	11	67,000	0 (cylindrical)	Yes
Parsons NS	Yingli Panda	4.2	31,000	10	No
Middlebury	SunPower	6.8	34,000	30	No
Appalachian St.	Sanyo	8.2	51,500	0 (horizontal)	No

* 25° is a combined angle because of the two arrays. The largest array was mounted at 22° and the smaller array at 35°.

4.3. Results Summary

Out of the 10 contests, six of them were very valuable to this research project. Unbiased measurements and equal contests amongst all houses provided a realistic perspective of affordable net-zero energy housing. With insight from the Purdue INhome, specific energy consumption values were used to compare and contrast different systems used. In the end, off-the-shelf engineering systems such as super-efficient HVAC units, heat pump hot water heaters, and properly designed photovoltaic arrays can affordably enable a house to become net-zero.

CHAPTER 5. DISCUSSION AND CONCLUSION

Many of the associated contests within the 2011 Solar Decathlon had valuable design ideas and technologies that are recognized to affordably save energy in the housing sector. These energy saving techniques may not be applicable to every building in the country due to different climate regions and energy prices. Nevertheless, energy consumption depicted in a typical home can still be reduced by using the design methods set forth in Chapter 3. Specifically, the three step design method in which the INhome utilized to reach net-zero. This method and information discovered from contests concludes that affordable, net-zero energy housing is possible today.

5.1. Step One - Building Envelope

The first point of the overarching design method discussed in this thesis is orienting a house properly with the surrounding environment and making sure the building envelope is constructed with extraordinary design methods. The greatest opportunity of energy savings in buildings are developed early on, when designing the building envelope. Moreover, these methods focus on insulation levels, air leakage, floor plan layout, fenestration, and overall footprint of the building. Additional planning in the form of energy modeling is necessary to ensure a net-zero home will become a reality by pin-pointing energy consumption prior to actually building a real house.

5.2. Step Two – Minimize Energy Loads

After the building has been properly oriented, insulated, and designed to become a net-zero energy building, the internal electrical loads must be considered. The second step must focus on everything from miscellaneous appliance loads to water heating. Specific to this research, the mechanical, water heating, and appliance loads of a design can make a big difference.

5.2.1. Mechanical

The average home uses 54 percent of all energy on heating and cooling. However, this is one of the most difficult percentages to generalize because of the vast climate regions in this country. Nonetheless, two vastly applicable factors existed while operating in the autumn Washington DC climate. A house's ability to combat high humidity levels and keep comfortable temperatures was a suitable metric in order to determine HVAC effectiveness and affordability.

Contest results revealed that many teams could not dehumidify effectively with the given weather conditions. Many teams overcooled their houses in attempt to keep indoor relative humidity within 60 percent. This constant operation consumed a lot of unnecessary electricity and narrowed many chances of reaching net-zero. The few teams that were capable of mastering both indoor relative humidity and temperature became scoring leaders. However, there was a drastic cost difference in the top performing HVAC systems.

Houses with separate mini-split mechanical and dehumidification systems performed very well, but were also very expensive. The traditional, off-the-shelf forced air system utilized in the Purdue INhome performed flawlessly and was the second lowest-priced system of all 19 teams. This statistic alone revealed the simplicity, affordability, and performance of this system. When designing for a net-zero energy home, a high efficiency HVAC system, similar to the INhome's should be considered.

5.2.2. Water Heating

One of the greatest findings from researching the Solar Decathlon was the fact that five of the seven teams that reached net-zero used heat pump water heaters. This is due to the fact that weather during the contest was not ideal for solar thermal systems. The contest results is a great indication of how much electricity can saved by using these heaters as a typical house consumes 13 percent of all energy for heating water. With concern to human hygiene, heat pump water heaters provided consistent hot water time after time.

Heat pump water heaters are more affordable, reliable, and easier to install than solar thermal systems. Numerically speaking, a heat pump water heater will use one unit of electricity to produce two – three units of hot water, depending on the manufacturer. On the other hand, a typical 40 gallon electric water heater will consume one unit of electricity to produce one unit of hot water.

As stated earlier, the competition week was fairly cloudy, with only four days reaching over 500 W/m2 of global horizontal solar radiation. The lack of sunshine during the competition proved difficult for the teams without heat pump water heaters to reach net-zero. Houses equipped with solar thermal collectors had to use back-up resistant electric water heaters to earn hot water points. These back-up heaters ranged in size from 2kW to 4.5kW. On the other hand, teams with a heat pump water heater used on average a little more than 2 kWh of electricity a day.

Without sunlight, a 2kW back-up electric resistance water heater could only actively heat water for a little over an hour each day with the same amount of energy a heat pump water heater uses. With that same amount of energy, a heat pump water heater can provide hot water all day long. Most importantly, heat pump water heaters cost significantly less than standard residential solar thermal collectors. When designing for a net-zero energy home or retrofitting an older home, a heat pump water heater should be considered.

5.2.3. Appliances

Another electrical load necessary for human survival and hygiene are appliances. The biggest determination in appliance energy usage is how often each appliance is used and if the appliance is Energy STAR rated or not. A common thought is to use smaller appliances to reduce energy consumption. For the typical American family, this myth should be dispelled because the cost of smaller, super-efficient appliances does not offer the homeowner significant energy savings. Newer, full-size Energy STAR rated appliances offer more savings and are more functional overall.

Moreover, the amount of energy consumed by standard-sized appliances is decreasing year after year. Appliance manufacturers are constantly delivering smarter and more energy efficient appliances. In addition, many appliance manufacturers are designing, testing, and manufacturing these appliances in the United States.

For example, the heat pump water heater used in the INhome was built by General Electric. With the assistance from the 2009 American Recovery Act, General Electric has been able to revive manufacturing efforts at their Louisville Appliance Park manufacturing plant in Louisville, KY and brings this cutting-edge technology closer to home (DOE, 2012). All GE heat pump water heaters are now manufactured in the United States, employing thousands of Americans every day.

5.3. Step Three – Optimize Energy Production

In order to make an attempt to affordably reach net-zero energy status, the size of the photovoltaic array, electricity consumption of the house, and cost of the photovoltaic array had to be determined as best as possible. In other words, because on-site renewable energy is expensive, the previous two net-zero design methodologies must be accomplished accordingly to match the array size with the house's energy consumption characteristics. This research indicated that keys to becoming net-zero through energy production alone are having a large enough array and ensuring that modules are installed at the best tilt angle possible.

5.4. Conclusion

Unfortunately, the nine day competition, in which data was collected for this research, limited annual performance data collection of net-zero energy housing. On the other hand, ongoing research will be conducted in the INhome to gather year-round information. To do so, INhome has been placed in a Lafayette, IN neighborhood and will continue to be monitored for many years to come. A real family, not directly associated with Purdue University will be living within the home. Information collected will provide a clear performance review of the INhome and how well it operates annually. The fact that the INhome has been successfully blended into a real-life neighborhood is a testament of the simple adaptations that can be made to current residential construction.

In all, there were very important and applicable methodologies that can be realized from the Solar Decathlon to mitigate the 22 percent of all energy consumed through the residential sector in the United States. Utilizing the three step design methodology for a net-zero energy building is an overall approach that will ultimately reduce the cost of building a net-zero energy building. Furthermore, utilizing affordable and high-efficiency HVAC systems, heat pump water heaters, and appliances can bring largely affect whether a house reaches net-zero or not. Affordable net-zero energy buildings can be built today with commitment from design professionals, manufacturers, and home owners.

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APPENDICES

Appendix A: INhome Energy Spreadsheet

Energy Consuming Device	Demand Power, W	Day - 9 (hrs)	Day - 9 Energy	Day - 10 (hrs)	Day - 10 Energy	Day - 11 (hrs)	Day - 11 Energy	Day - 12 (hrs)	Day - 12 Energy	Day - 13 (hrs)	Day - 13 Energy	Day - 14 (hrs)	Day - 14 Energy	Day - 15 (hrs)	Day - 15 Energy	Day - 16 (hrs)	Day - 16 Energy	Day - 17 (hrs)	Day - 17 Energy
GE Refrigerator - Freezer	300	6	1800	6	1800	6	1800	6	1800	8	2400	6	1800	8	2400	6	1800	6	1800
GE Clothes Dryer	1500	0	0	0.6	900	0.6	900	0.6	900	0	0	1.2	1800	0	0	1.2	1800	0.6	900
GE Clothes Washer	800	0	0	1	800	1	800	1	800	0	0	2	1600	0	0	2	1600	1	800
GE Dish Washer	400	0	0	1.5	600	0	0	1.5	600	0	0	1.5	600	0	0	1.5	600	1.5	600
Lighting	829	4	3316	4	3316	4	3316	4	3316	4	3316	6	4974	4	3316	4	3316	1	829
Sony Bravia TV	122	0	0	3	366	4	488	4	488	7	854	6	732	6	732	7	854	3	366
Sony Blu-Ray player BDP-S380	20	0	0	3	60	4	80	4	80	7	140	6	120	6	120	7	140	3	60
Sony Sound Bar HT-CT550W	30	0	0	0	0	0	0	0	0	3	90	3	90	3	90	0	0	0	0
Computer	120	0	0	7	840	11	1320	12	1440	9	1080	8	960	9	1080	11	1320	7	840
Data Acquisition	72	24	1728	24	1728	24	1728	24	1728	24	1728	24	1728	24	1728	24	1728	24	1728
Internet Router	5	24	120	24	120	24	120	24	120	24	120	24	120	24	120	24	120	24	120
eMonitor	2	24	48	24	48	24	48	24	48	24	48	24	48	24	48	24	48	24	48
Trane ComfortLinkII	8	24	192	24	192	24	192	24	192	24	192	24	192	24	192	24	192	24	192
GE Oven	2100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
GE Induction Cooktop 11"	2275	0	0	1	2275	0	0	1	2275	2	4550	0	0	2	4550	0	0	1	2275
GE Advantium Microwave	1000	0	0	0	0	0	0	0	0	2	2000	0.2	200	2	2000	0	0	0	0
Trane XL20i	1250	5	6250	5	6250	5	6250	5	6250	5	6250	5	6250	5	6250	5	6250	5	6250
Trane AHU	150	5	750	5	750	5	750	5	750	5	750	5	750	5	750	5	750	5	750
Trane Fresh Effects ERV	150	3	450	3	450	3	450	3	450	3	450	3	450	3	450	3	450	3	450
Ducted Dehumidifier	600	2	1200	3	1800	3	1800	3	1800	3	1800	3	1800	3	1800	3	1800	3	1800
GE GeoSpring	500	5	2500	3	1500	3.5	1750	4.5	2250	5	2500	4.5	2250	3.5	1750	4.5	2250	4.5	2250
Zoeller Ejector Pump	450	0.25	112.5	0.25	112.5	0.25	112.5	0.25	112.5	0.25	112.5	0.25	112.5	0.25	112.5	0.25	112.5	0.25	112.5
Main Water Pump	1500	1	1000	2	1500	2	1500	2	1500	1	1000	2	1500	2	1000	2	1500	2	1500
Fire Pump	3000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2 Ceiling Fans (60W ea.)	120	8	960	8	960	8	960	8	960	8	960	8	960	8	960	8	960	8	960
Miscellaneous Loads	50	1	50	1	50	1	50	1	50	1	50	1	50	1	50	1	50	1	50
Daily Energy Consumption (Wh)		20477		26418		24415		27910		30391		29087		29499		27641		24681	

Installed PV Size =	**8.64**	**kW**
Total Energy Use (Week) =	240.51	kWh
Avg. Daily Energy Req'd =	26.72	kWh/day
Avg. Daily Sunshine Hrs =	4.00	hrs
Required PV Array Size =	6.68	kW
Final Efficiency =	0.79	
Corrected PV Size =	***8.48***	***kW***
Total Surplus Demand =	***0.16***	***kW***

Efficiency Factors	
Mounting Angle PV efficiency reduction	0.90
Central Inverter Efficiency	0.95
Wire loss	0.95
Sky Clearness Factor	1.00
Dust & Dirt	0.97
Final Efficiency	0.79

TEAM PURDUE INHOME

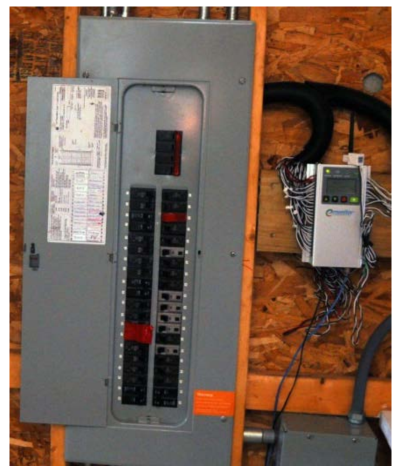
Appendix B: Competition Scoring

	Overall	ENG	Affordability	Comfort Zone	Hot Water	Energy Balance	Appliances	Home Entertain	Market Appeal	Comm	ARCH
1 Maryland	951.15	89 (4)	$336,336	96.139 (3)	100 (T1)	100 (T1)	99.798 (2)	97.847	94	88	96
2 Purdue	931.39	87 (6)	$257,854	98.529 (2)	98.75 (3)	100 (T1)	97.333 (6)	96.563	91	83	80
3 New Zealand	919.06	93 (1)	$303,468	77.347 (12)	100 (T1)	100 (T1)	86.478 (14)	96.079	93	84	95
4 Middlebury College	914.81	82 (11)	$282,570	81.633 (7)	97.375 (5)	83.229 (4)	98.269 (4)	98.560	95	90	93
5 Ohio State	903.94	88 (5)	$285,982	98.652 (1)	100 (T1)	88.586 (3)	93.093 (10)	90.206	83	80	86
6 SCI-Arc/Caltech	899.49	91 (2)	$262,495	88.2 (6)	100 (T1)	100 (T1)	93.707 (9)	98.333	69	82	89
7 Illinois	875.72	73 (16)	$291,813	61.833 (17)	98.25 (4)	100 (T1)	99.955 (1)	95.858	89	79	83
8 Tennessee	859.13	90 (3)	$470,465	80.343 (9)	100 (T1)	100 (T1)	99.591 (3)	96.065	77	78	92
9 Massachusetts	856.35	84 (9)	$267,913	77.896 (11)	96.375 (6)	96.16 (2)	92.349 (12)	94.362	92	49	87
10 Canada	836.42	83 (10)	$286,051	61.347 (18)	99.5 (2)	56.013 (5)	95.599 (7)	97.569	87	81	80
11 Florida Int'l	833.16	72 (17)	$368,072	81.07 (8)	86 (9)	100 (T1)	82.94 (16)	89.655	85	76	88
12 Appalachian State	832.5	80 (13)	$342,325	72.663 (15)	100 (T1)	36.58 (6)	81.6 (17)	97.847	90	89	94
13 Parsons NS Stevens	828.82	85 (8)	$229,890	78.724 (10)	100 (T1)	35.169 (7)	91.984 (13)	88.939	86	72	91
14 Tidewater Virginia	774.91	64 (19)	$325,613	92.881 (4)	93.75 (T7)	0 (T9)	98.255 (5)	96.586	88	67	82
15 Team China	765.47	86 (7)	$345,610	91.816 (5)	93.75 (T7)	3.59 (8)	86.438 (15)	90.938	81	71	90
16 Team Belgium	709.84	74 (15)	$249,568	64.597 (16)	89.688 (8)	0 (T9)	95.065 (8)	96.994	67	41	84
17 Team New York	677.36	81 (12)	$411,302	56.401 (19)	62.5 (11)	0 (T9)	72.592 (19)	94.682	76	85	84
18 Team New Jersey	669.35	78 (14)	$389,304	74.628 (13)	5.687 (10)	0 (T9)	92.411 (11)	86.275	64	50	81
19 Team Florida	619.01	66 (18)	$334,186	73.191 (14)	0 (12)	0 (T9)	74.445 (18)	90.788	84	58	85

Appendix C : eMonitor

Each circuit had a corresponding current transformer, which senses current flowing to each circuit throughout the house. Data is constantly sent to an online server via a home internet connection. The screenshot below illustrates how energy consumption and production within the house can be monitored online. The free software can also be used to set up alerts if a circuit consumes energy at abnormal rates.

Wireless monitoring



eMonitor physical connection

eMonitor

Channel Setup Worksheet: eMonitor-44

Serial #: EM1 A1

Installation Address: PURDUE INHOME

Monitored Panel: MAIN PANEL
(e.g.: Main Panel, Subpanel, 3rd floor panel)

Breaker Number(s)	eMonitor Channel	Power Source?	Breaker Size (A)	Circuit Label	Circuit Size: 120V	Circuit Size: 240V 1 CT	Circuit Size: 240V 2 CT	CT/Sensor Type: White (20A)	CT/Sensor Type: Black (50A)	CT/Sensor Type: Large (150A)
	1			Main Power						
	2			Main Power						
38,40	3	✓	40	PV BACK FEED		✓			✓	
1	4		30	WATER HEATER			✓		✓	
3	5		30	WATER HEATER			✓		✓	
5	6		20	XL20;			✓		✓	
7	7		20	XL20;			✓		✓	
9	8		30	AIR HANDLER.			✓		✓	
11	9		30	AIR HANDLER			✓		✓	
13	10		20	OVEN			✓	✓		
15	11		20	OVEN			✓	✓		
17	12		40	COOKTOP			✓		✓	
19	13		40	COOKTOP			✓		✓	
29	14		30	CLOTHES DRYER			✓		✓	
31	15		30	CLOTHES DRYER			✓		✓	
21	16		15	DISHWASHER	✓			✓		
2	17		20	KITCHEN	✓			✓		
4	18		20	KITCHEN	✓			✓		
6	19		15	REFRIGERATOR	✓			✓		
8	20		15	MICROWAVE	✓			✓		
10	21		20	KITCHEN PLUGMOLDS	✓			✓		
12	22		15	LAUNDRY/KITCHEN LIGHTS	✓			✓		
14	23		15	GARAGE/RESEARCH SHED	✓			✓		
16	24		20	BATH GFCI	✓			✓		

Circuit Size: Check 1 of 3 boxes. CT/Sensor Type: Check 1 of 3 boxes.

eMonitor™

Channel Setup Worksheet: eMonitor-44

Serial #: EM1 A1

Installation Address: PURDUE INhome

Monitored Panel:

(e.g.: Main Panel, Subpanel, 3rd floor panel)

Breaker Number(s)	eMonitor Channel	Power Source?	Breaker Size (A)	Circuit Label	Circuit Size (Check 1 of 3 boxes) 120V	240V 1 CT	240V 2 CT	CT/Sensor Type (Check 1 of 3 boxes) White (20A)	Black (50A)	Large (150A)
18	25		15	BATH LIGHTING	✓			✓		
20	26		15	MASTER RECEPTACLES	✓			✓		
22	27		15	OFFICE RECEPTACLES	✓			✓		
24	28		15	BEDROOM LIGHTING	✓			✓		
28	29		15	BROWALL / KITCHEN LIGHTS	✓			✓		
30	30		15	LIVING ROOM	✓			✓		
32	31		20	GARAGE GFCI/CONTROLS	✓			✓		
34	32		20	EXTERIOR	✓			✓		
~~33~~	~~33~~		~~20~~	~~WASTE PUMP~~	~~✓~~			~~✓~~		
~~35~~	~~34~~		~~20~~	~~WATER SUPPLY PUMP~~	~~✓~~			~~✓~~		
	35									
	36									
	37									
	38									
	39									
	40									
	41									
	42									
	43									
	44									

Appendix D: Engineering Contest Breakdown

Engineering Contest Overall Scoring

Note: Numbers in boxes (4,3,2,1) are not additive. See Appendix E for question descriptions

		New Zealand, 101	Sci-Arc/Caltech, 402	Tennessee, 202	Maryland, 304	Ohio State, 404	Purdue, 201	China, 303	Parsons NS Stevens, 204	Massachusetts, 401	Canada, 301	Middlebury, 203	New York, 403	Appalachian State, 205	New Jersey, 104	Belgium, 302	Illinois, 305	Florida Int'l, 206	Florida, 102	Tidewater Virginia, 103
Functionality	A1	4	4	4	3	4	4	4	4	4	4	4	2	4	1	4	3	4	2	3
	A2	3	3	4	3	4	4	3	3	4	4	3	1	2	2	3	2	1	2	1
	A3	3	3	4	4	4	4	3	3	4	3	3	2	2	2	2	2	1	2	2
Efficiency	B1	3	3	2	4	4	2	4	4	3	3	4	3	3	3	3	2	2	2	1
	B2	3	4	4	3	4	3	4	3	3	2	3	3	2	2	3	4	2	2	2
Innovation	C1	4	4	4	4	4	3	4	2	2	2	2	4	4	3	2	2	2	2	2
	C2	4	4	3	4	3	2	3	3	2	3	2	2	3	2	2	2	2	1	2
Reliability	D1	4	4	3	3	3	3	2	3	2	3	3	2	3	2	3	2	4	1	2
	D2	3	3	2	2	3	3	3	3	4	2	3	2	3	2	2	2	4	1	1
Documentation	E1	3	3	3	4	2	4	3	3	3	3	2	3	2	3	1	1	1	1	1
	E2	3	3	4	4	3	4	3	3	1	3	3	3	4	2	2	2	2	1	2

Appendix E: Team Purdue Detailed Engineering Scorecard

PURDUE							
ENGINEERING		TEAM SCORE				POINTS	
		APPROACH	EQUALS	EXCEEDS	ECLIPSES	/100	
CONTEST CRITERIA		0-60%	61-80%	81-90%	91-100%		**OBSERVATIONS/COMMENTS**
A.	**FUNCTIONALITY**						
1	Do the systems function as intended?				X		everything appear to be working
2	Does the HVAC system maintain indoor air quality via contaminant control, fresh air ventilation, or both?				X		ERV and demand control ventilation are very good. The biowall is an interesting addition.
3	Does the HVAC system maintain uniform thermal comfort conditions via temperature control, humidity control, air movement, and a successful distribution system design?				X		Strong independent controls with good distribution
B.	**EFFICIENCY**						
1	Relative to conventional systems, how much energy will the systems save over the course of an entire year?		X				reasonable thermal envelope with good windows, good demand control ventilation, reasonable savings
2	Do the HVAC and lighting controls facilitate a reduction in energy consumption during an entire year of operation?			X			Trane controls throughout should give solid performance, ERV has good demand control, but controls are not in one place. Lighting with no occupancy sensors shown.
C.	**INNOVATION**						
1	Were any unique approaches used to solve design challenges?			X			biowall-dehumidifier combination for design climate.
2	Do the proposed innovations have true market potential?		X				Not sure if there will be any energy savings but a nice asthetic feature.
D.	**RELIABILITY**						
1	How long are the systems expected to operate at a high level of performance?			X			Systems are off the shelf except for biowall and should be reliable.
2	How much maintenance is required to keep them operating at a high level?			X			biowall maintenance is uncertain but everything else has easy access to maintenance items and is off the shelf
E.	**DOCUMENTATION**						
1	Did the drawings, construction specifications, energy analysis results and discussion, and audiovisual engineering presentation enable the jury to conduct a preliminary evaluation of the design prior to its arrival at the competition site?				X		E-analysis was good and made comparison to a reference case The construction documents were nice and concise.
2	Did the drawings, construction specifications, energy analysis results and discussion, and audiovisual engineering presentation accurately reflect the constructed project as assembled on the competition site?				X		Built as specified
Total						87	

Appendix F : INhome Estimated Cost

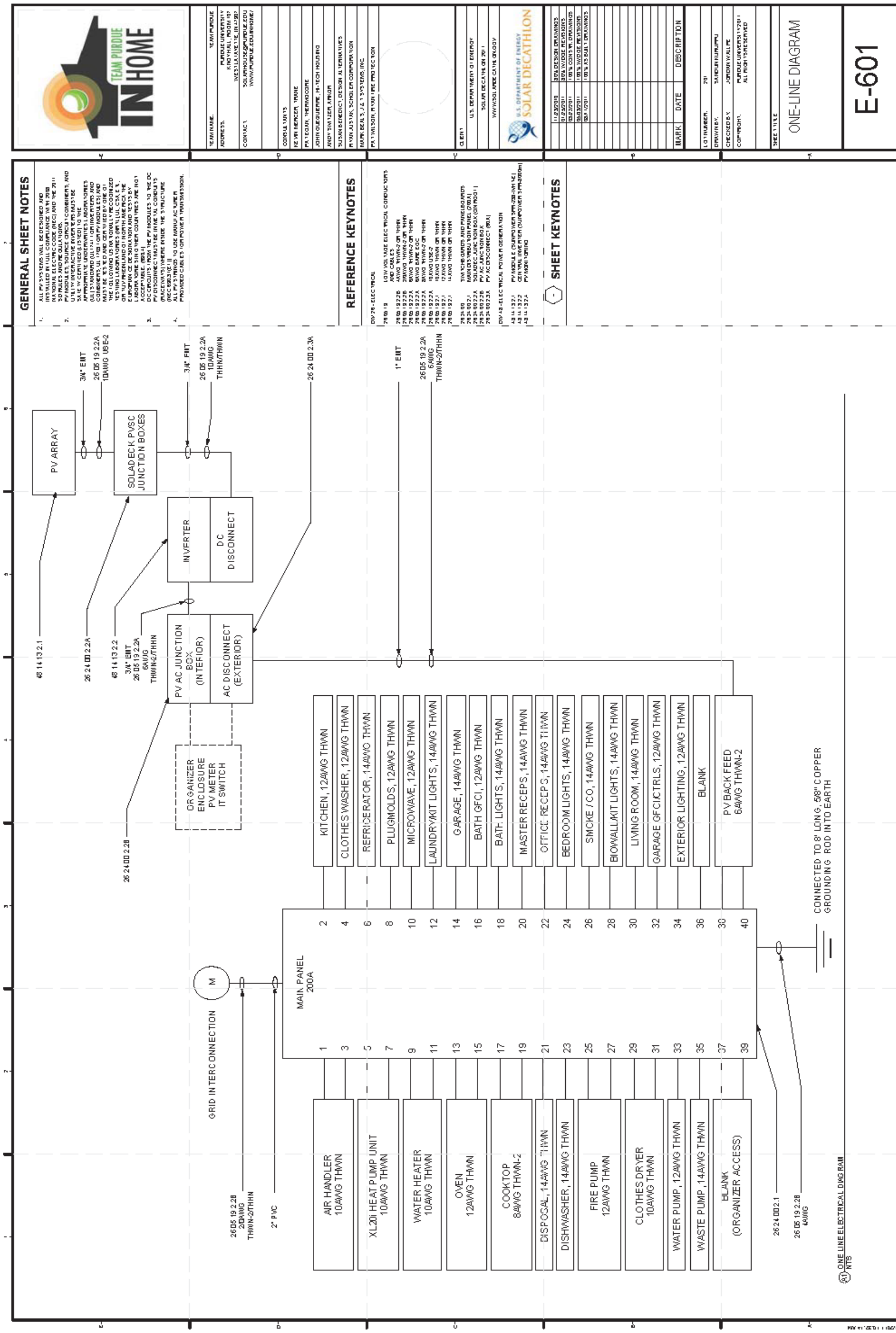
Brief Description	Qty	Unit	Material Cost	Labor Cost	Other Costs	TOTALS	Grand Totals	Sum
010000 General Requirements								$ 6,924
Typical House Crane	2	Day	$ -	$ 660	$ 2,225	$ 2,885	$ 5,770	
SUBTOTAL							$ 5,770	
Div. 1 Contingency	20%						$ 1,154	
020000 Existing Conditions								$ 876
Site Survey	0.5	Acre	$ 75	$ 1,600	$ 77	$ 1,752	$ 876	
SUBTOTAL							$ 876	
Div. 2 Contingency	0%						$ -	
060000 Wood, Plastic, Composites								$ 28,722
Typ Wood Ramps	320	S.F.	$ 1.43	$ 3.73	$ -	$ 5.16	$ 1,651	
Interior Walls	230	L.F.	$ 4.79	$ 8.70	$ -	$ 13.49	$ 3,103	
Custom	7	Ea.	$ 88.50	$ 29.50	$ 12.00	$ 130	$ 910	
Wood framing 4:12	220	L.F.	$ 0.61	$ 0.82	$ -	$ 1.43	$ 315	
Subfloors, 3/4" plywood	1000	SF Flr.	$ 0.64	$ 0.63	$ -	$ 1.27	$ 1,270	
deck framing 2" x 8"	1680	L.F.	$ 1.18	$ 0.71	$ -	$ 1.89	$ 3,175	
deck framing 5/4" x 6"	1035	S.F.	$ 2.59	$ 1.22	$ -	$ 3.81	$ 3,943	
SIPS 4", 8-1/4"	2116	S.F.	$ 3.20	$ 0.85	$ 1.50	$ 5.55	$ 11,744	
SUBTOTAL							$ 26,111	
Div. 6 Contingency	10%						$ 2,611	
070000 Thermal and Moisture Protection								$ 13,051
	5900	S.F.	$ 0.08	$ 0.11	$ -	$ 0.2	$ 1,121	
Cement wood-fiber plank	2116	S.F.	$ 2.55	$ 0.78	$ -	$ 3.3	$ 7,046	
Typ metal gutters	100	L.F.	$ 1.14	$ 2.26	$ -	$ 3.4	$ 340	
Timberline Cool Series Energy Saving Shingles.	13	Sq.	$ 145	$ 94.00	$ -	$ 239.0	$ 3,107	
Underlayment	13	Sq.	$ 13.15	$ 6.10	$ -	$ 19.3	$ 250	
SUBTOTAL							$ 11,865	
Div. 7 Contingency	10%						$ 1,186	
080000 Openings								$ 24,818
Garage: 8070 O.H. DOOR	1	Ea.	$ 1,250	$ -	$ -	$ 1,250	$ 1,250	
3 'x 6'8" CCA230	20	SF			$ 20.00	$ 20	$ 400	
3' x 6'8" CCV10020-LE	80	SF	$ 1		$ 20.00	$ 21	$ 1,640	
3' x 6'8" Pocket	20	SF			$ 15.75	$ 16	$ 315	
3' x 6'8" Passage	55.5	SF			$ 15.75	$ 16	$ 874	
3' x 6'8" TS210	20	SF			$ 20.00	$ 20	$ 400	
5' x7' Bi-Fold	35	SF			$ 15.75	$ 16	$ 551	
2'4" x 6'8" Passage	15	SF			$ 15.75	$ 16	$ 236	
4' x7' Bi-Fold	56	SF			$ 15.75	$ 16	$ 882	
2' x 2' KOLBE A21 A	1	Ea.	$ 490			$ 490	$ 490	
4' x 1'6" KOLBE AR41 A	5	Ea.	$ 1,308		$ -	$ 1,308	$ 6,540	
3' x2' KOLBE A31 A	3	Ea.	$ 1,441			$ 1,441	$ 4,323	
2' x 4' KOLBE CXW14	4	Ea.	$ 695			$ 695	$ 2,780	
SUBTOTAL							$ 20,682	
Div. 8 Contingency	20%						$ 4,136	
090000 Finishes								$ 16,272
Typ 1/2" Gypsum Board	3600	S.F.	$ 0.40	$ 1.01	$ -	$ 1.41	$ 5,076	
Typical Exterior Paint	1	S.F.	$ 0.16	$ 0.71	$ -	$ 0.87	$ 1	
Typical Interior Trim Paint	1	L.F.	$ 0.17	$ 1.03	$ -	$ 1.20	$ 1	
Typical Interior Paint	1	S.F.	$ 0.21	$ 0.52	$ -	$ 0.73	$ 1	
laminated	856	S.F.	$ 3.84	$ 3.29	$ -	$ 7.13	$ 6,103	
Baseboards and casing	600	L.F.	$ 2.22	$ 0.97		$ 3.19	$ 1,914	
Ceramic Tile floor	64	S.F.	$ 2.25	$ 5.00	$ -	$ 7.25	$ 464	
SUBTOTAL							$ 13,560	
Div. 9 Contingency	20%						$ 2,712	

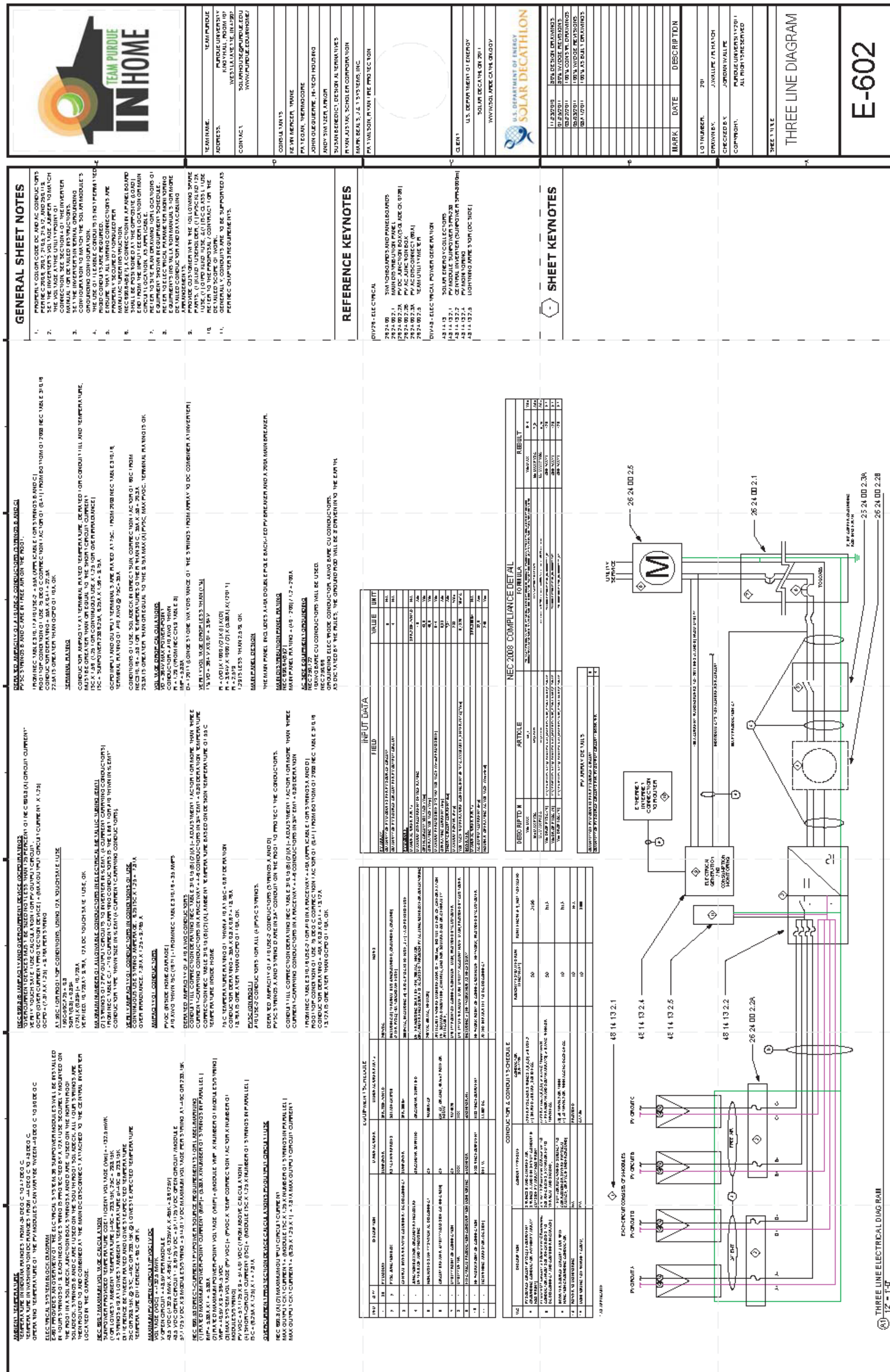
Brief Description	Qty	Unit	Material Cost	Labor Cost	Other Costs	TOTALS	Grand Totals	Sum
100000 Specialties								$ 480
cost per toilet & shower	1	Unit	$ -	$ -	$ 400	$ 400	$ 400	
SUBTOTAL							$ 400	
Div. 10 Contingency 20%	20%						$ 80	
110000 Equipment (Appliances - 11 31 00)								$ 6,077
GE Disposer GFC535T	1	Ea.			$ 134	$ 134	$ 134	
GE Washer PFWS4600L	1	Ea.		$ 900		$ 900	$ 900	
GE Dryer PFDS450ELOWW	1	Ea.		$ 850		$ 850	$ 850	
GE Oven JTS10SPSS	1	Ea.			$ 808	$ 808	$ 808	
GE DW GLDS5768VSS	1	Ea.			$ 570	$ 570	$ 570	
GE Refrig GTH18ISXSS	1	Ea.			$ 750	$ 750	$ 750	
GE icemaker IM4A	1	Ea.			$ 47	$ 47	$ 47	
GE Induction PHP900SMSS	1	Ea.			$ 1,099	$ 1,099	$ 1,099	
GE Mic PSA1201RSS	1	Ea.			$ 630	$ 630	$ 630	
SUBTOTAL	1	Ea.					$ 5,788	
Div. 11 Contingency 5%	5%						$ 289	
120000 Furnishings (Mounted/Permanent)								$ 23,268
Custom Cabinets	46	L.F.	$ 345	$ 32.50	$ -	$ 378	$ 17,365	
Bath cabinets, excl. counters & fixtures, maximum	3	L.F.	$ 50	$ 32.50	$ -	$ 83	$ 248	
Typical Vanity Top	1	Ea.	$ 208	$ 33.50	$ -	$ 242	$ 242	
QUARTZ SURFACE FABRICATIONS, LG (High Max)	24	L.F.	$ 23	$ 21.00	$ 20.00	$ 64	$ 1,536	
SUBTOTAL							$ 19,390	
Div. 12 Contingency	20%						$ 3,878	
130000 Special Construction								$ 6,600
BIO-WALL	1	Ea.	$ 6,000			$ 6,000	$ 6,000	
SUBTOTAL							$ 6,000	
Div. 13 Contingency 10%	10%						$ 600	
210000 Fire Suppression								$ 3,561
Wet Fire Sprinkler	981	SF	$ 1.25	$ 1.50	$ 0.55	$ 3.30	$ 3,237	
SUBTOTAL							$ 3,237	
Div. 21 Contingency 10%	10%						$ 324	
220000 Plumbing								$ 29,406
Rough Plumbing Supply	981	SF	$ -	$ -	$ 8.35	$ 8.35	$ 8,191	
Plastic Rough Waste	981	SF	$ -	$ -	$ 2.75	$ 2.75	$ 2,698	
WATER HEATER	1	Ea.	$ 1,400			$ 1,400	$ 1,400	
DOMESTIC WATER PIPING	1				$ 7,500	$ 7,500	$ 7,500	
Centrifugal Pump 1D880	1	Ea.			$ 320	$ 320	$ 320	
Shower	1	Ea	$ 2,325	$ 157	$ -	$ 2,482	$ 2,482	
Water Closet K3577	1	Ea.			$ 134	$ 134	$ 134	
BATH AND SHOWER K-713	1	Ea.			$ 424	$ 424	$ 424	
BATH/SHOWER FIXTURES K-496, K-304, K11660	1	Ea.			$ 350	$ 350	$ 350	
BATH AND SHOWER Trim K-T16233-4	1	Ea.			$ 284	$ 284	$ 284	
Bath Drain K-11660	1	Ea.			$ 56	$ 56	$ 56	
Kitchen Sink Faucet	1	Ea.	$ 200			$ 200	$ 200	
SINKS K-3180	1	Ea.			$ 365	$ 365	$ 365	
Sinks K-2882	1	Ea.			$ 101	$ 101	$ 101	
SUBTOTAL							$ 24,505	
Exception: The cost estimator and juries will disregard all containers and associated equipment, such as pressure pumps, that would be unnecessary if city water and sewer services were available on the competition site. Therefore, these components shall be noted as "Temporary for Competition Purposes" in renderings and other graphical representations. Note that all structures and surfaces that surround the containers will be evaluated by the cost estimator and juries								
	20%						$ 4,901	

Brief Description	Qty	Unit	Material Cost	Labor Cost	Other Costs	TOTALS	Grand Totals	Sum
230000 Heating, Ventilating and Air Conditioning								$ 7,809
Heat Pump Trane XL20i	1	Ea.	$ 1,000			$ 1,000	$ 1,000	
Trane ERV TERVR100A9P00A	1	Ea.	$ 750			$ 750	$ 750	
AHU TAM8A0C36H315A	1	Ea.			$ 3,000	$ 3,000	$ 3,000	
TraneTFD235ALAH000C	1	Ea.	$ 500			$ 500	$ 500	
DEHUMIDIFIER Ultra-Aire	1	Ea.			$ 80	$ 80	$ 80	
Ductwork Estimate	981	SF	$ -	$ -	$ 1.20	$ 1	$ 1,177	
SUBTOTAL							$ 6,507	
Div. 23 Contingency 20%	20%						$ 1,301	
250000 Integrated Automation								$ 10,487
Trane/Schlage sensors, thermostat control unit	1		$ 7,034	$ 1,000	$ 1,500	$ 9,534	$ 9,534	
C02 Sensor TR9294-A-L								
C02 Sensor TR9292-A-L								
Temp/Hum ALC/IOK~2-H300-R								
Temp/Hum BA/IOK-2-H300-D-BB								
Outside Temp/Hum BA/IOK-2-H300-0-BB								
Control Relay								
Transformer Panel PSH300A								
VOC Sensor BA/BS3X-VOClO-BNK								
VOC Sensor BAjVOCIO-D-BB								
Controller/Router ME812U-LGR								
Point Expander MEX016U								
Point Expander MEX48U								
WebCtrl Software								
Control Panel A36N24MPP								
Current Switch H800 Hawkeye								
SUBTOTAL							$ 9,534	
Div. 25 Contingency 10%	10%						$ 953	
260000 Electrical								$ 68,967
Installation, Distribution, rough electrical work	1269	SF			$ 3.65	$ 4	$ 4,632	
Typical Load Panel	1	Ea.	$ 480	$ 480	$ -	$ 960	$ 960	
Sub Panel	1	Ea.			$ 500	$ 500	$ 500	
SunPower SPR-238	238	DCw	$ 2.50	$ 0.75		$ 774	$ 27,846	
SunPower SPR-8000m	8	Kw	$ 675	$ 250		$ 925	$ 7,400	
Typical PV Rough in electrical system	1	Ea.	$ 500	$ 500	$ -	$ 1,000	$ 1,000	
Generic PV Mounting Rack, per solar panel	41	Ea.	$ 220	$ 20	$ -	$ 240	$ 9,840	
Kichler Ceiling Mounted Light 206NI	2	Ea.			$ 15	$ 15	$ 30	
Forecast Pacifica 4 light pendant F1930-36	1	Ea.			$ 414	$ 414	$ 414	
Forecast Pacifica pendant light F1932-36	3	Ea.			$ 156	$ 156	$ 468	
Kichler 3 light pendant 2752NI	2	Ea.			$ 266	$ 266	$ 532	
Forecast Pacifica Wall Sconce F5467-36U	2	Ea.			$ 140	$ 140	$ 280	
American Fluo. Corp, 48'' light T8	1	Ea.			$ 100	$ 100	$ 100	
LED Lighting Inc. Versa Bar No. V10WW12V	4	Ea.			$ 40	$ 40	$ 160	
Kichler Pira Bath Vanity, No. 10424BAW	1	Ea.			$ 250	$ 250	$ 250	
Craftmade Ceiling Fan w. 5 Blades No. 225705	2	Ea.			$ 75	$ 75	$ 150	
Zilotek 120V LED Strip No. 0014-0002	3	Ea.			$ 25	$ 25	$ 75	
Custom Biowall, 2.6 W LED Grow Lights	8	Ea.			$ 150	$ 150	$ 1,200	
Outdoor Wall Light, No. F8491-68NV	8	Ea.			$ 125	$ 125	$ 1,000	
Kichler Deck Light No. 15064AZT	8	Ea.			$ 55	$ 55	$ 440	
Kichler Accent Light No. 15384BKT	3	Ea.			$ 65	$ 65	$ 195	
SUBTOTAL							$ 57,472	
Div. 26 Contingency	20%						$ 11,494	
280000 Electronic Safety and Security								$ 505
Generic Fire Alarm System	1	Ea.	$ 221	$ 238	$ -	$ 459	$ 459	
SUBTOTAL							$ 459	
Div. 28 Contingency 10%	10%						$ 46	

Brief Description	Qty	Unit	Material Cost	Labor Cost	Other Costs	TOTALS	Grand Totals	Sum
310000 Earthwork								$ 9,910
Abs Footings 10" Circular	4	Ea.	$ 7.25	$ 5.00		$ 12.25	$ 49	
Abs Footings 16"Circular	17	Ea.	$ 16.00	$ 5.00		$ 21.00	$ 357	
Abs Footings 16" x 16" Square	12	Ea.	$ 6.75	$ 5.00		$ 11.75	$ 141	
Abs Footings 18.5' x 18.5" Square	15	Ea.	$ 8.00	$ 5.00		$ 13.00	$ 195	
Abs Footings 20 x20 Square	2	Ea.	$ 10.35	$ 5.00		$ 15.35	$ 31	
Abs Footings 24 x 24 Square	34	Ea.	$ 14.50	$ 5.00		$ 19.50	$ 663	
Large Wooden	9	EA.	$ 5.00	$ 86.38		$ 91.38	$ 822	
Small Screw Jacks	75	EA.			$ 80.00	$ 80.00	$ 6,000	
SUBTOTAL							$ 8,258	
Div. 31 Contingency 20%	20%						$ 1,652	
320000 Exterior Improvements								$ 121
Ground Cover	1,100	SF	$ -	$ -	$ 0.10	$ 0.10	$ 110	
SUBTOTAL							$ 110	
Div. 32 Contingency 10%	10%						$ 11	
							TOTAL	$ 257,854

Appendix G : Photovoltaic Drawings




TEAM PURDUE
INHOME
GENERAL SHEET NOTES
REFERENCE KEYNOTES
SHEET KEYNOTES
EQUIPMENT SCHEDULE
CONDUCTOR & CONDUIT SCHEDULE
INPUT DATA
NEC 2008 COMPLIANCE DETAIL
PV ARRAY DETAILS
U.S. DEPARTMENT OF ENERGY
SOLAR DECATHLON
MARK
DATE
DESCRIPTION
THREE LINE DIAGRAM
E-602
THREE LINE ELECTRICAL DIAGRAM
12" = 1'-0"
48 14 13 2.1
48 14 13 2.4
48 14 13 2.5
48 14 13 2.2
26 24 00 2.2A
26 24 00 2.5
26 24 00 2.1
26 24 00 2.3A
26 24 00 2.2B
UTILITY SERVICE
M

AMBIENT TEMPERATURE
TEMPERATURE IN INDIANA RANGES FROM -34 DEG C TO 47 DEG C.
TEMPERATURE IN WASHINGTON DC RANGES FROM -44 DEG C TO 48 DEG C.
OPERATING TEMPERATURE OF THE PV MODULES CAN VARY BETWEEN -40 DEG C TO 50 DEG C

ELECTRICAL SYSTEM BLOCK DIAGRAM
E-601 PROVIDES AN OVERVIEW OF THE ELCTRICAL SYSTEM. 36 SUNPOWER MODULES WILL BE INSTALLED IN FOUR STRINGS OF 9. EACH NEGATIVE STRING IS PROTECTED BY A 12A FUSE SECURELY MOUNTED ON THE ROOF IN A SOLADECK JUNCTION BOX. STRINGS A AND D ARE FUSED ON THE NORTH ROOF SOLADECK. STRINGS B AND C ARE FUSED ON THE SOUTH ROOF SOLADECK. ALL FOUR STRINGS ARE THEN ROUTED TO AND COMBINED AT THE MAIN DC DISCONNECT ATTACHED TO THE CENTRAL INVERTER LOCATED IN THE GARAGE.

NEC 690.7 MAXIMUM VOLTAGE CALCULATION
SUNPOWER PROVIDED TEMPERATURE COEFFICIENT VOLTAGE (Voc) = -132.5 mV/K
(FOR LOWEST AMBIENT TEMPERATURE) -40C = 233.15K, 25C = 298.15K
4 STRINGS of 9 AT LOWEST AMBIENT TEMPERATURE of -40C or 233.15K
DIFFERENCE BETWEEN RATED AND LOWEST EXPECTED TEMPERATURE
25C OR 298.15K @ STC, -40C OR 233.15K @ LOWEST EXPECTED TEMPERATURE
TEMPERATURE DIFFERENCE = 65 C OR K

MAXIMUM PV OPEN CIRCUIT (PVOC) V DC
VOLTAGE (VOC) = -132.5 MV/ K
V OPEN CIRCUIT = 48.5V PER MODULE
48.5 V DC (-132.5 MV/K X -65K) = (-0.1325V/K X -65K = 8.6125V)
48.5 V DC OPEN CIRCUIT + 8.6125 V DC = 57.1125 V DC OPEN CIRCUIT / MODULE
57.1125 V DC X 9 MODULES/STRING = 514.01 V DC MAXIMUM VOLTAGE PER STRING AT -40C OR 233.15K

NEC 690.53 DIRECT-CURRENT PV POWER SOURCE REQUIREMENTS FOR LABEL/MARKING
(1) RATED MAXIMUM POWER-POINT CURRENT (IMP) = (5.88A X NUMBER OF STRINGS IN PARALLEL)
IMP = 5.88A X 1 = 5.88A
(2) RATED MAXIMUM POWER-POINT VOLTAGE (VMP) = (MODULE VMP X NUMBER OF MODULES/STRING)
VMP = 40.5V X 9 = 364.5 VDC
(3) MAX SYSTEM VOLTAGE (PV VOC) = (PVOC X TEMP CORRECTION FACTOR X NUMBER OF MODULES/STRING)
PV VOC = 57.1125 X 9 = 514.01 VDC (FROM ABOVE CALCULATION)
(4) SHORT-CIRCUIT CURRENT (ISC) = (MODULE ISC X 1.25 X NUMBER OF STRINGS IN PARALLEL)
ISC = (6.25A X 1.25) X 1 = 7.81A

OVERCURRENT PROTECTION DEVICE CALCULATIONS PV OUTPUT CIRCUIT FUSE

NEC 690.8 (A) (2) MAXIMUM OUTPUT CIRCUIT CURRENT
MAX OUTPUT CKT CURRENT = (MODULE ISC X 1.25 X NUMBER OF STRINGS IN PARALLEL)
MAX OUTPUT CKT CURRENT = (6.25 X 1.25 X 1) = 7.81A MAX OUTPUT CIRCUIT CURRENT

NEC 690.8 (B) AMPACITY AND OVERCURRENT DEVICE (OCPD) RATINGS
"OVERCURRENT DEVICES MUST BE SIZED NOT LESS THAN 125 PERCENT OF NEC 690.8 (A) CIRCUIT CURRENT"
VERIFY TOUCH SAFE FUSE CALCULATION FOR PV OUTPUT CIRCUIT :
OCPD (OVER CURRENT PROTECTION DEVICE) = (MAX OUTPUT CIRCUIT CURRENT X 1.25)
OCPD = (7.81A X 1.25) = 9.76A PER STRING

AT 50C FOR ROOFTOP CONDITIONS, USING 12A TOUCHSAFE FUSE
150C-50C/125 = 0.8
SQRT(0.8) = 0.894
(12A) X (0.894) = 10.728A
VERFIED: 10.728A > 9.76A; 12A DC TOUCH SAFE FUSE, OK

MAXIMUM NUMBER OF ALLOWABLE CONDUCTORS IN ELECTRICAL METALLIC TUBING (EMT)
(2) STRINGS OF 2 PV OUTPUT CIRCUITS TO INVERTER IN ¾ EMT. (4 CURRENT CARRYING CONDUCTORS)
FROM NEC TABLE C.1 - "10 CURRENT CARRYING CONDUCTORS IS THE LIMIT FOR #10 THWN IN ¾ EMT"
CONDUCTOR TYPE THWN SIZE IN ¾ EMT (4 CURRENT CARRYING CONDUCTORS).

VERIFY AMPACITY OF CONDUCTORS IN CONDITIONS OF USE
CONTINUOUS USE STRING AMPERAGE: 6.25 ISC X 1.25 = 7.81A
OVER IRRADIANCE: 7.81A X 1.25 = 9.765 A

AMPACITY OF CONDUCTORS

PVOC (INSIDE HOME/GARAGE)
#10 AWG THWN 75C (167F) - FROM NEC TABLE 310.16 = 35 AMPS

DERATED AMPACITY OF # 10 AWG CONDUCTORS
CONDUIT FILL CORRECTION DERATING NEC TABLE 310.15 (B) (2) (A) – ADJUSTMENT FACTOR FOR MORE THAN THREE CURRENT-CARRYING CONDUCTORS IN A RACEWAY = 4-6 CONDUCTORS IN 3/4" EMT = 0.80 DERATION TEMPERATURE CORRECTION NEC TABLE 310.15 (B) (2) (A), AMBIENT TEMPERATURE BASED ON DESIGN TEMPERATURE OF 55 C TEMPERATURE INSIDE HOME

75 C TEMPERATURE RATING OF THWN # 10 AT 55C = 0.67 DERATION
CONDUCTOR DERATING = 35A X 0.8 X 0.67 = 18.76A
18.76A IS GREATER THAN OCPD OF 10A. OK

PVSC (ON ROOF)
#10 USE-2 CONDUCTORS FOR ALL (4) PVSC STRINGS.

DERATED AMPACITY OF # 10 USE-2 CONDUCTORS (STRINGS A AND D)
PVSC STRINGS A AND STRING D ARE IN 3/4" CONDUIT ON THE ROOF TO PROTECT THE CONDUCTORS.

CONDUIT FILL CORRECTION DERATING NEC TABLE 310.15 (B) (2) (A) – ADJUSTMENT FACTOR FOR MORE THAN THREE CURRENT-CARRYING CONDUCTORS IN A RACEWAY = 4-6 CONDUCTORS IN 3/4" EMT = 0.80 DERATION

FROM NEC TABLE 310.16 USE-2 FOR #10 IN A RACEWAY = 40A (APPLICABLE FOR STRINGS A AND D)
ROOFTOP CONDITION OF USE 75 DEG C CORRECTION FACTOR OF (0.41) FROM BOTTOM OF 2008 NEC TABLE 310.16
CONDUCTOR DERATING = 40A X 0.8 X 0.41 = 13.12A
13.12A IS GREATER THAN OCPD OF 10A. OK

DERATED AMPACITY OF # 10 USE-2 CONDUCTORS (STRINGS B AND C)
PVSC STRINGS B AND C ARE IN FREE AIR ON THE ROOF.

FROM NEC TABLE 310.17 #10 USE-2 = 55A (APPLICABLE FOR STRINGS B AND C)
ROOFTOP CONDITION OF USE 75 DEG C CORRECTION FACTOR OF (0.41) FROM BOTTOM OF 2008 NEC TABLE 310.16
CONDUCTOR DERATING = 55A X 0.41 = 22.5A
22.5A IS GREATER THAN OCPD OF 10A. OK

TERMINAL RATING

CONDUCTOR AMPACITY AT TERMINAL RATED TEMPERATURE, DERATED FOR CONDUIT FILL AND TEMPERATURE, MUST BE GREATER THAN OR EQUAL TO THE SHORT CIRCUIT CURRENT
ISC X 1.56 (1.25 FOR CONTINUOUS USE X 1.25 FOR OVER IRRADIANCE)
ISC = SUNPOWER 238 6.25A, 6.25A X 1.56 = 9.75A

OCPD INPUT AND OUTPUT TERMINALS ARE RATED AT 75C. FROM 2008 NEC TABLE 310.16,
TERMINAL RATING OF #10 AWG @ 75C= 35A

CONDITIONS OF USE: SOLADECK IN DIRECT SUN, CORRECTION FACTOR OF 60C FROM
NEC310.16 = .58 FOR TEMPERATURES OTHER THAN 30 C , 35A X .58 = 20.3A
20.3A IS GREATER THAN OR EQUAL TO THE 9.75A MAX (A) PVSC, MAX PVOC. TERMINAL RATING IS OK

VOLTAGE DROP CALCULATIONS
VD = 364V MAX POWER-POINT
CONDUCTOR = #10 AWG THWN
R = 1.29 (FROM NEC CH.9 TABLE 8)
IMP = 5.88A
D= 120FT (LONGEST ONE WAY DISTANCE OF THE STRINGS FROM ARRAY TO DC COMBINER AT INVERTER)

VERIFY VOLTAGE DROP LESS THAN (1%)
1% VD = 364 V X 0.01 = 3.64V

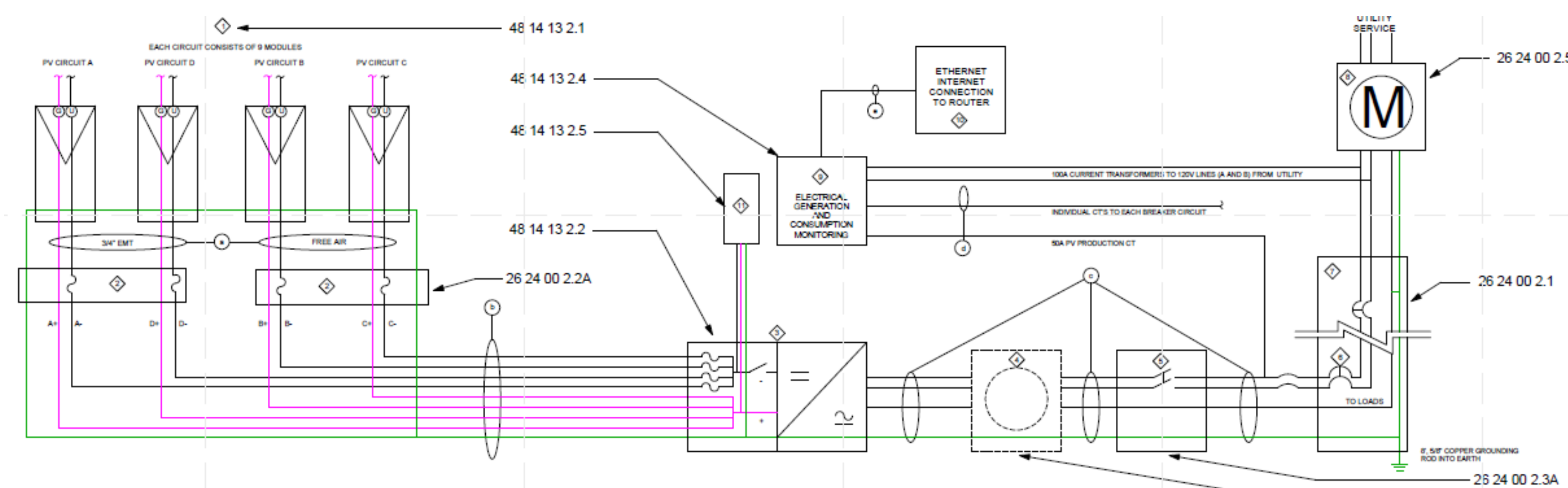
R = (VD) X 1000 / (2) X (I) X (D)
R = 3.64V X 1000 / (2) X (5.88A) X (120FT)
R = 2.579
1.29 IS LESS THAN 2.579. OK

MAIN PANEL DESIGN

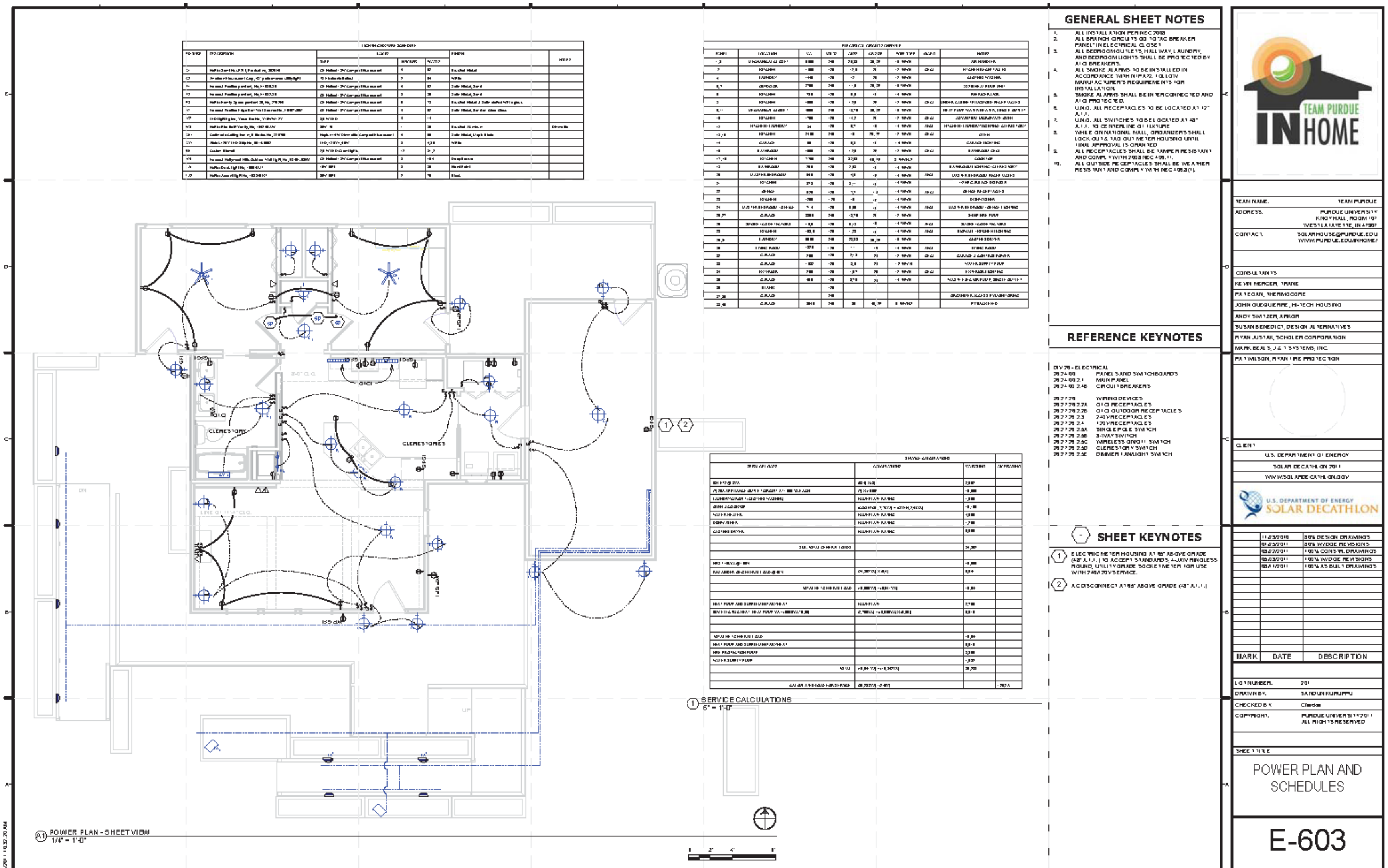
THE MAIN PANEL INCLUDES A 40A DOUBLE POLE BACK-FED PV BREAKER AND A 200A MAIN BREAKER.

MAIN DISTRIBUTION PANEL RATING
NEC 690.64(B)(2)
MAIN PANEL RATING = (40 + 200) / 1.2 = 200A

AC SIDE EQUIPMENT GROUNDING
NEC 250.122
10AWG BARE CU CONDUCTORS WILL BE USED.
NEC 250.66
GROUNDING ELECTRODE CONDUCTOR: 4AWG BARE CU CONDUCTORS.
AS DICTATED BY THE RULES, THE GROUND ROD WILL BE 8' DRIVEN INTO THE EARTH.



THREE LINE ELECTRICAL DIAGRAM



GENERAL SHEET NOTES
1. ALL INSTALLATION PER NEC 2008
2. ALL BRANCH CIRCUITS GO TO AC BREAKER PANEL IN ELECTRICAL CLOSET
3. ALL BEDROOM OUTLETS, HALLWAY, LAUNDRY, AND BEDROOM LIGHTS SHALL BE PROTECTED BY AFCI BREAKERS.
4. ALL SMOKE ALARMS TO BE INSTALLED IN ACCORDANCE WITH NFPA72. FOLLOW MANUFACTURER'S REQUIREMENTS FOR INSTALLATION.
5. SMOKE ALARMS SHALL BE INTERCONNECTED AND AFCI PROTECTED.
6. U.N.O. ALL RECEPTACLES TO BE LOCATED AT 12" A.F.F.
7. U.N.O. ALL SWITCHES TO BE LOCATED AT 48" A.F.F. TO CENTERLINE OF FIXTURE
8. WHILE ON NATIONAL MALL, ORGANIZERS SHALL LOCK OUT & TAG OUT METER HOUSING UNTIL FINAL APPROVAL IS GRANTED
9. ALL RECEPTACLES SHALL BE TAMPER RESISTANT AND COMPLY WITH 2008 NEC 406.11.
10. ALL OUTSIDE RECEPTACLES SHALL BE WEATHER RESISTANT AND COMPLY WITH NEC 406.8(1).
REFERENCE KEYNOTES
DIV 26 - ELECTRICAL
26 24 00 PANELS AND SWITCHBOARDS
26 24 00 2.1 MAIN PANEL
26 24 00 2.4B CIRCUIT BREAKERS
26 27 26 WIRING DEVICES
26 27 26 2.2A GFCI RECEPTACLES
26 27 26 2.2B GFCI OUTDOOR RECEPTACLES
26 27 26 2.3 240V RECEPTACLES
26 27 26 2.4 120V RECEPTACLES
26 27 26 2.5A SINGLE POLE SWITCH
26 27 26 2.5B 3-WAY SWITCH
26 27 26 2.5C WIRELESS GINGLE SWITCH
26 27 26 2.5D CLERESTORY SWITCH
26 27 26 2.5E DIMMER / DAYLIGHT SWITCH
SHEET KEYNOTES
1 ELECTRIC METER HOUSING AT 68" ABOVE GRADE (48" A.F.F.) TO ACCEPT STANDARD, 4-JAW RINGLESS ROUND, UTILITY GRADE SOCKET METER FOR USE WITH 240/120V SERVICE.
2 AC DISCONNECT AT 68" ABOVE GRADE (48" A.F.F.)
1 SERVICE CALCULATIONS
6" = 1'-0"
A1 POWER PLAN - SHEET VIEW
1/4" = 1'-0"
CLERESTORIES
CLERESTORY
GFCI
TEAM PURDUE
INHOME
TEAM NAME: TEAM PURDUE
ADDRESS: PURDUE UNIVERSITY
KNOY HALL, ROOM 107
WEST LAFAYETTE, IN 47907
CONTACT: SOLARHOUSE@PURDUE.EDU
WWW.PURDUE.EDU/INHOME/
CONSULTANTS
KEVIN MERCER, TRANE
PAT EGAN, THERMOCORE
JOHN GUEGUIERRE, HI-TECH HOUSING
ANDY SWITZER, ARKOR
SUSAN BENEDICT, DESIGN ALTERNATIVES
RYAN JUSTAK, SCHOLER CORPORATION
MARK BEALS, J & T SYSTEMS, INC.
PAT WILSON, RYAN FIRE PROTECTION
CLIENT
U.S. DEPARTMENT OF ENERGY
SOLAR DECATHLON 2011
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CHECKED BY: Checker
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POWER PLAN AND SCHEDULES
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