# Assessing the Engineering Performance of Purdue University's INhome as an Example of Affordable Net-Zero Energy Housing

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**ABSTRACT**

The Solar Decathlon is a well-known international competition that challenges teams of university students to design, build, and showcase solar powered houses that produce as much energy as they consume on an annual basis. This paper reviews the performance of Purdue University's INhome, which earned a 2nd place overall finish in the 2011 Solar Decathlon. Comparisons are made to other homes in the competition to provide a context for understanding how the INhome performed during the contest. The results show that appropriate use of current technologies can lead to homes that are affordable, comfortable, and net-zero in terms of their annual demand for electricity from the electric grid.

## Introduction

The average American household spends $2,200 on energy annually (EIA 2012). Taken as a whole, the residential sector in the United States consumes more than 22% of all energy in the United States (EIA 2009). This is largely unnecessary; hence the need for educating homeowners about how energy can be saved in new or existing homes. That is the goal for the U.S. Department of Energy's Solar Decathlon, a high profile international contest that invites 20 teams of university students to design, build, and demonstrate highly efficient homes that use solar power to generate as much energy as they consume on an annual basis.

Since its inception in 2002, the Solar Decathlon has been held every other year in September on the National Mall in Washington, DC where it draws in excess of 300,000 spectators plus significant national and international media coverage (DOE 2011). It is an impressive spectacle to see the "solar village" that is created in a little more than one week's time. The 20 homes are limited to 1,000 $ft^2$ in size but are fully operational in every respect.

Table 1 summarizes the ten different contests that were part of the 2011 competition. Half of these contests are based on direct measurements of the home's performance and the other half are subjective (evaluated by juries). The winning team is the one with the highest cumulative score. The highlighted contests in Table 1 were targeted during this research.

**Table 1. Contests in the 2011 Solar Decathlon**

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

The contests in the 2011 Solar Decathlon created a powerful research platform for comparing affordable, energy saving systems in solar-powered housing. The solar village had 19 unique houses of similar size and age in one geographic location that competed against each other for nine days during September of 2011. Even with particularly cloudy weather, several teams demonstrated their houses could still reach net-zero during this week with solar energy (no other alternative energy sources were permitted). In the end, the contest results helped identify the best combination of affordable, energy-saving technologies and designs.

The Affordability Contest was introduced this year and required each home to be within an estimated builder's cost of $250,000. This came about because previous Solar Decathlons did not have a limit on cost and several houses reached the million dollar mark. This was detrimental to the purpose of the contest because overly expensive or extravagant homes are not feasible options for the average American family. This new Affordability Contest was implemented to encourage teams to select economically feasible solutions for creating net-zero energy houses. Each house had the same $250,000 target for construction and was identically measured and reviewed without bias.

**Purdue University's INhome**

Figure 1 shows Purdue University's INhome as it was displayed during the 2011 Solar Decathlon in Washington, D.C. The INhome's aesthetics had a practical, familiar, and comfortable look that was well received by the judges and more than 18,000 members of the general public who came in for a tour (DOE 2011). The home also performed extremely well from a technical perspective, finishing near the top in every one of the measured contests with a 2nd place overall finish.

**Figure 1. The 2nd place INhome on display at West Potomac Park in Washington, D.C.**

Credit: Jim Tetro (U.S. Department of Energy Solar Decathlon)

The Purdue INhome was designed using an iterative three-step process to optimize overall performance and minimize costs:

- Step 1 - Passive design: orientation, insulation, day lighting, and overall layout
- Step 2 - Mechanical design: properly sized HVAC, efficient appliances, and lighting
- Step 3 - Solar panels: selecting solar modules to achieve net-zero energy

Step one identified appropriate orientation and insulation levels with respect to the Lafayette, IN climate. The house was oriented due south to gain maximum sunlight exposure for day lighting and solar energy collection. Overhangs shaded all south-facing windows to reduce direct energy gains during the summer, but enabled direct energy gain during the winter. Appropriate levels of insulation and air tightness inside the INhome were attained using a structural insulated panel system (SIPS). The SIPS provided 4-inch (R-24) walls and an 8-inch (R-50) ceiling.

Step two minimized internal energy loads by selecting appropriate mechanical systems and appliances. A highly efficient central air conditioning system with heat recovery minimized the energy for heating and cooling. All appliances in the home were full sized, but specifically selected for their energy efficiency and ENERGY STAR® rating.

Step three maximized energy production through a properly designed photovoltaic array. Computations accounted for wire loss, tilt angle, sky clearness, dust/dirt, inverter and module efficiencies, and sunshine hours. An acceptable number of sunshine hours for both Lafayette, IN and Washington D.C. was 4.5 kWh/m$^2$/day (NREL 2004). To be conservative, 4.0 kWh/m$^2$/day was used as the design value.

Of the 100 houses that have competed in the Solar Decathlon since 2002, none have been placed into a typical residential neighborhood; where the bulk of Americans live. Keeping true to its goal of being a "real home for a real family", the INhome was placed in Chatham Square, a community in Lafayette, IN that is part of a broader neighborhood revitalization effort. Figure 2 shows the INhome at its final location. The home will be on display through the summer of 2012 and then sold to a private resident. After that it will be monitored to support research into the long term performance of cost effective homes that are supposed to be net-zero in terms of their annual demand for electricity from the electric grid.

**Figure 2. INhome in the Chatham Square Community, Lafayette, IN**

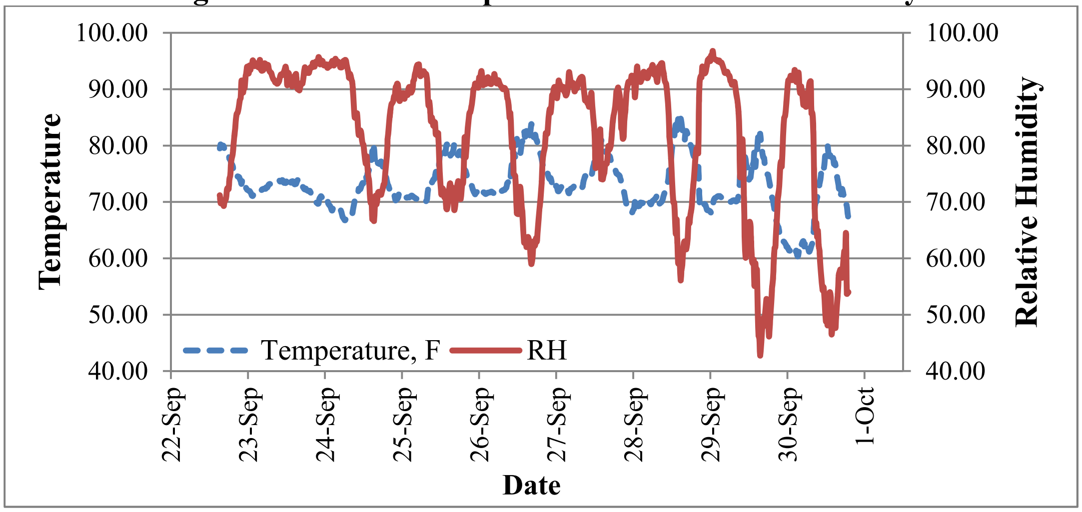

## Results

The competition officials released all scoring documentation for each house at the conclusion of the Solar Decathlon 2011. Both quantitative and qualitative contest results were made publicly available through the Department of Energy's Solar Decathlon website. Data collection for this research had some limitations. The most significant factor was that the Solar Decathlon competition only took place over nine days. A better way to compare competing houses would be to evaluate the homes in the same location over a calendar year.

## Weather

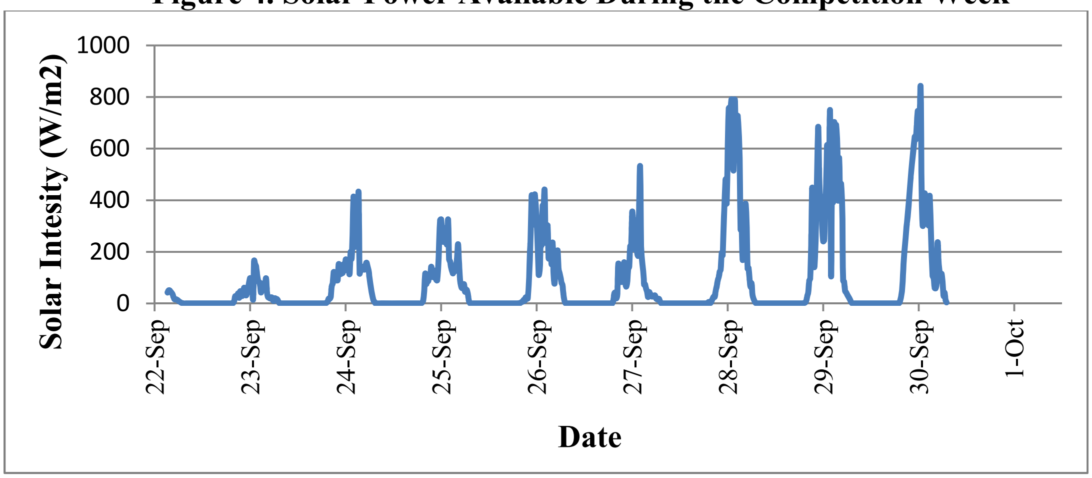
The weather during the 2011 Solar Decathlon was hot, humid, and cloudy. These weather conditions provided less than ideal operating conditions for solar energy collection and HVAC operations. Figure 3 displays the weather conditions that all teams had to contend with. The nine day competition week saw outdoor temperatures of approximately 80°F each day and high relative humidity during both the night and day.

**Figure 3. Outdoor Temperature and Relative Humidity**




The sky was overcast for the majority of the competition. This reduced the opportunity for teams to reach net-zero and stretched out the final scoring to the last hour of data collection. The amount of global horizontal solar radiation available during the competition is illustrated in Figure 4. Only four days surpassed 500 W/m$^2$. The lack of sunshine limited each photovoltaic array to about half-capacity, as photovoltaic modules are tested and rated at 1000 W/m$^2$ conditions[1]. Mainly due to the inclement weather, only seven teams reached net-zero.

**Figure 4. Solar Power Available During the Competition Week**




[1] Both PTC and STC photovoltaic module rating standards use a solar irradiance of 1000 W/m$^2$.

After evaluating houses and the contests associated with 2011 Solar Decathlon, it was found that the three dominant contests impacted the final outcome of the competition. The Comfort Zone, Hot Water, and Energy Balance Contests were most affected by poor weather conditions in Washington, D.C. Houses that were designed to perform in unseasonably wet weather had a distinct advantage.

**Comfort Zone**

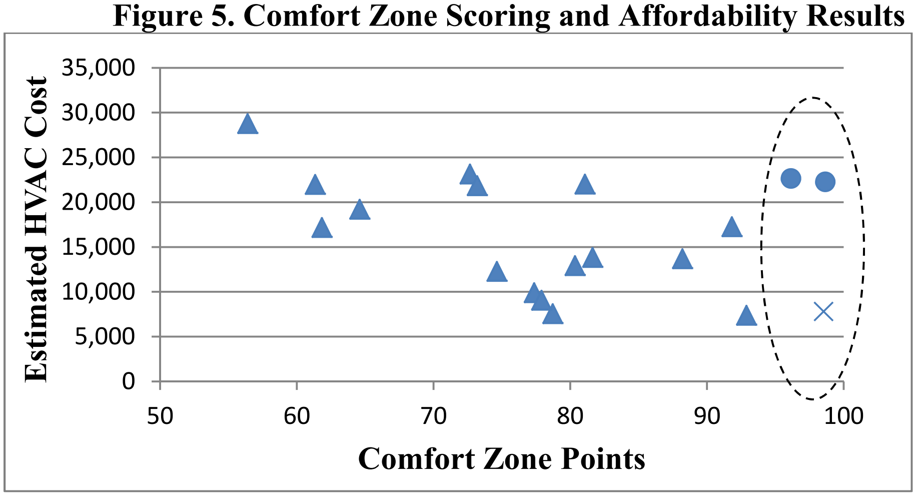
The Comfort Zone contest challenged each house to be within very specific temperature and relative humidity set points. During specified hours the houses had to be between 71-76 °F and under 60 percent relative humidity. A typical day would have the Comfort Zone recordings start one hour after public tours, around 3 P.M., and continue through the night until public tours started again the next morning, around 9 A.M.

A majority of the houses had difficulty earning points in the Comfort Zone Contest. Most teams utilized mini-split HVAC systems because of their ease of application in smaller houses and their precise temperature control. Historically, mini-split systems have been very popular in the Solar Decathlon competition. Of the 19 homes in 2011, 13 had some version of a mini-split HVAC system.

The weather during the 2011 competition impacted efforts to maintain reasonable humidity levels in each house. Relative humidity levels, as seen in Figure 3, were very high at night, over 90 percent. Dehumidification efforts by several teams were unsuccessful partially because of shorter run times with mini-split units. Dehumidification was not possible when mini-split units were not running. Therefore, many teams tried to stay within the temperature limits and disregarded relative humidity as the temperature was worth more (75% of the Comfort Zone points).

Figure 5 summarizes HVAC system cost as a function of performance in the Comfort Zone Contest. The circle on the graphs identifies the three teams that earned 95 or more points for maintaining the prescribed temperature and humidity limits. The top two scoring teams, Maryland and Ohio State, used mini-split systems that performed exceptionally well, but at additional cost. These additional costs were incurred because of the custom dehumidification systems used by both teams, which did an exceptional job of removing moisture from the indoor air, while at the same time keeping within the temperature set points. However, each HVAC system was valued at over $20,000.

**Figure 5. Comfort Zone Scoring and Affordability Results**



The Purdue INhome system is marked by an "X" in Figure 5. The HVAC system inside the INhome was a two ton, off-the-shelf system with a two compressor heat pump unit rated at SEER 19. At low stage cooling, the smaller compressor consumed 450 watts. It was paired with an air handling unit that had a variable speed drive fan. This system kept below the 60 percent relative humidity threshold for 95 percent of the competition while keeping within the temperature set points. The dehumidification function of this system enabled the fan to continuously dehumidify at a slow speed that used only 30 watts when running.

Figure 5 illustrates that under the scoring system used in the competition, the best performing and most affordable system was the forced air heat pump from the INhome. Figure 5 also suggests that mini-splits would not perform ideally in humid climates unless a separate dehumidification system was present. The results contradict the notion that radical innovations are needed by showing that a central HVAC system can achieve satisfactory performance for a net-zero house when it is sized properly and is capable of both cooling and dehumidification.

## Hot Water

One of the 10 Solar Decathlon contests simulated hot water usage in a typical home by requiring hot water draws from the shower on a regular schedule. Each draw required at least 15 gallons of water at 110 °F within 10 minutes. Most competition days had two to three draws at different times. There were two different types of hot water systems used in the competition: solar thermal systems and heat pump water heaters.

The cloudy weather during the competition proved difficult for teams with solar thermal systems; which operate best on sunny days. Without direct sunlight, homes with solar thermal systems did not have enough hot water capacity and resorted to back-up electric resistance water heating. The electric coils ranged in size from 2 kW to 4.5 kW and provided roughly a one to one exchange of electricity to hot water.

A heat pump water heater has a distinct advantage because it has at least a two to one thermodynamic advantage in energy performance when compared to electric resistance heating. When a heat pump water heater consumes one unit of electricity it produces at least two units of hot water. In other words, a heat pump water heater produces twice the hot water using the same amount of electricity.

The dominance of the heat pump water heaters in the 2011 Solar Decathlon is clearer when viewed in the context of the energy balance contest, which evaluated whether a home produced more energy than it consumed. Only seven teams reached net zero during for the energy balance contest and five of those seven teams used heat pump water heaters. Teams that used solar thermal systems wasted precious kWh on making hot water.

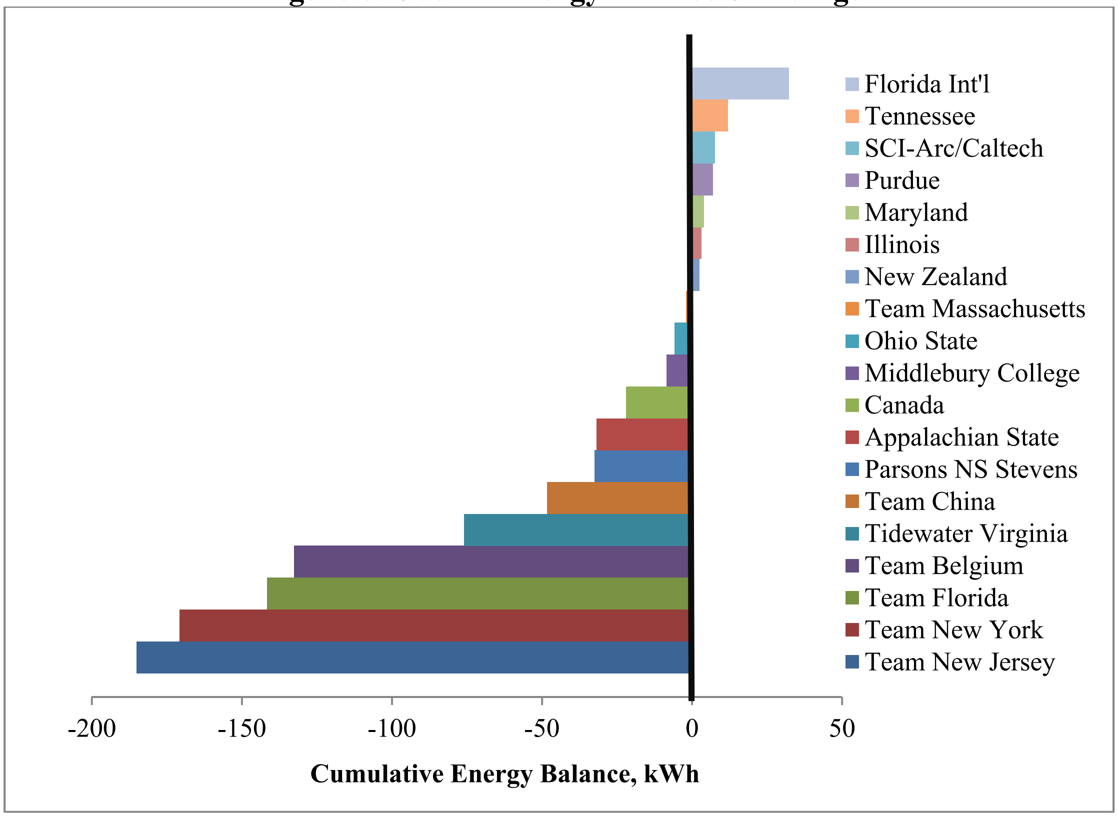
Cost was another factor in the Solar Decathlon. The average stand-alone solar thermal system cost $7,100 as compared to the average of $1,500 for a heat pump water heater. A combination of energy performance and cost made heat pump water heaters the best solution for the solar decathlon, but the overall answer for a homeowner might not be so clear cut.

Outside the Solar Decathlon competition, heat pump water heaters are not always so helpful. During cold weather they capture energy at ambient room temperature and then release colder air to the home. In this undesirable situation, the energy for water heating is coming from the furnace used to heat the house. Under these circumstances a solar thermal system may be the best overall option because it would not "steal" heat from the home to heat water.

**Energy Balance**

The Energy Balance contest quantitatively determined whether or not a house was net-zero during the week long competition. The amount of electricity both generated and consumed by the house was recorded the same way for each house. The size of the photovoltaic array, electricity consumption of the house, and cost of the photovoltaic array were also considered to determine which system affordably reached net-zero energy status. As illustrated in Figure 6, only seven out of nineteen teams were able to overcome the cloudy week and reach net-zero.

**Figure 6. Overall Energy Balance Standings**




A sample of the photovoltaic installations is summarized in Table 2. The table includes the nominal array size in kW, the installed cost, the mounting angle, and whether or not the home achieved net zero. The teams selected give a brief sample of the different photovoltaic design approaches. Of the seven teams that managed to reach net zero, the average array size was 8.4kW and cost was $48,700 ($5.80/Watt). The other 12 teams had an average array size of 6.9kW and cost of $31,250 ($4.50/Watt). It is clear that some houses simply did not have an adequately sized array to reach net-zero.

**Table 2. Sample of Photovoltaic Arrays**

| Team | Array Size, kW | Installed Cost, $ | Tilt angle, ° | Net-Zero? |
|---|---|---|---|---|
| Tennessee | 11.0 | 67,000 | 0 (cylindrical) | Yes |
| New Zealand | 6.3 | 28,500 | 15 | Yes |
| Purdue | 8.6 | 56,000 | 25 | Yes |
| Parsons NS | 4.2 | 31,000 | 10 | No |
| Middlebury | 6.8 | 34,000 | 30 | No |
| Appalachian St. | 8.2 | 51,500 | 0 (horizontal) | No |

Other factors helped determine if a home reached net zero, such as tilt angle. As highlighted in Table 2, Appalachian State had an adequate array size, but their modules were mounted horizontally and it appeared to reduce the power output accordingly. The rule of thumb for a fixed mount array is to have the tilt angle matching the latitude, which optimizes annual energy output (NREL 2011). The latitude for Washington D.C. is 38°.

From looking at the competition data it is easy to see that overall Energy Balance performance is partially based on array size and tilt angle as stated above. However, no two houses were identical and unique features of each home gave that specific home its value to the homeowners. That was the difference between New Zealand and Middlebury, as Middlebury consumed more electricity and had a larger living area (997 S.F.) compared to New Zealand (774 S.F.). The energy balance difference between the two houses was only 10 kWh. All teams that reached net-zero did a good job of estimating electric loads of their individual houses for the competition. This is a critical step in sizing a photovoltaic array and must be done early in the design process.

## Engineering

The Engineering contest evaluated how well each team designed their house with respect to functionality, efficiency, innovation, reliability, and documentation. This was a qualitative contest determined by a jury. Several teams took unique engineering design approaches, while others focused on meeting the prescriptive competition requirements. After looking at the Engineering Contest results, a few general observations can be made:

1. Innovation was an important sub-category of the Engineering Contest. Three out of four teams earning full innovation points finished in first, second, and fourth place in the Engineering contest. The CHIP house from SCI-Arch/Caltech, which finished second in the Engineering Contest, featured an advanced home automation system that integrated energy monitoring, HVAC control, optimization of decathlon scoring, and 3d cameras all in an easy-to use interface. The team even developed an iPad app.
2. Teams that scored well in the Engineering Contest had a better chance of becoming net-zero. Of the top six teams in the Engineering contest, five reached net-zero during the competition.
3. The top two teams in the documentation sub-contest were also the top two teams in the overall Engineering contest, which shows the importance of professionally developing construction documents and materials.

## Conclusion

The Solar Decathlon engages teams of talented university students in a competition that has important ramifications for the United States. It seeks to demonstrate that highly efficient solar powered homes can be comfortable, attractive, and affordable. The results of the 2011 competition were evaluated to identify specific factors that contributed to optimal performance. It was found that modern central air conditioning systems with proper dehumidification can perform very well in hot and humid weather. Secondly, it was found that a heat pump water heater will outperform a solar thermal water heating system under less than optimal solar conditions. The third finding was that photovoltaic arrays performed better when internal loads were correctly predicted and individual modules were mounted at the correct tilt angle. Finally, it was found that well-engineered houses earned higher overall scores, specifically for houses that had innovative features with market potential. Every team that participates in the Solar Decathlon is a winner because the competition helps demonstrate that solar housing can be practical and feasible using modern technologies and innovative designs.

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