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ABSTRACT

A net zero energy home was designed and built by Purdue University for the 2011 Solar Decathlon in Washington, DC. After earning a 2nd place finish in this international competition, the home was permanently located in Lafayette, IN and became a private residence. Since that time, energy monitoring equipment has measured both energy consumption of the home and energy generation by the solar photovoltaic panels. Three full years of data (2013 to 2015) have been collected to show that the home has met its original design goal for net zero energy. Beyond net zero, the data also shows interesting seasonal trends for HVAC, water heating, lighting, and other energy consuming devices. A survey of the current occupants provides further insight into how well features like indoor air quality, comfort, and aesthetics were incorporated into the overall design. The results suggest that a net zero energy home can be accomplished without sacrificing quality of life.

1. INTRODUCTION

A net zero energy home was created and built by a Purdue University student team for the 2011 Solar Decathlon. The goal of this competition was to design and build a home that took into account aesthetics, comfort, practicality, affordability, and energy efficiency. The term net-zero means that the total amount of energy used on an annual basis is equal to the amount of energy produced by a renewable energy source, such as solar power in this scenario. The Purdue entry was called the INhome, short for Indiana Home, because of the stated goal of showcasing advanced technologies in a practical residence that would appeal to the people from the Midwest.

After the Solar Decathlon competition, the INhome was moved to an affordable neighborhood in Lafayette, Indiana. Figure 1 is a street view of the home as it looks today. The south-facing roof in the photograph is covered in solar panels and is part of the INhome's 9.0 kW solar photovoltaic array that is comprised of 36, 240 watt solar panels. Although the INhome is still tied to the local electric grid, it was designed to provide all of its own electricity. The purpose of this paper is to evaluate the INhome's net zero performance after 3 full years of occupancy (2013-2015).

Figure 1: Street view of INhome

The INhome has many passive features, such as high levels of insulation and air sealing, which minimize energy consumption. Figure 1 shows the operable clerestory windows that provide day lighting and also, when open, allow for fresh air flow. The clerestory windows work in tandem with the large double-hung windows at ground level to encourage natural ventilation during appropriate seasons. The front porch and large roof overhangs provide external shading to the walls of the house are further examples of passive features that promote energy efficiency.

The INhome also has several active features that are installed to reduce energy consumption. Several web-based controllers automate the HVAC (heating, ventilating, and air conditioning) and security systems in the INhome. An energy recovery ventilator helps reduce heating and cooling loads. Also, high efficiency appliances were used to minimize electric loads in the kitchen and laundry. Together, the active and passive features were designed to make it possible for the INhome to be net zero.

Figure 2 is a floor plan for the INhome. It is a 92.9 square meter house that consists of a living room, kitchen, bathroom, 2 bedrooms, garage, and a utility room. The kitchen and living room is a combined great room with high vaulted ceilings that makes the space seem larger than it really is. The overall layout is compact, but offers a sustainable design without sacrificing modern comforts and amenities.

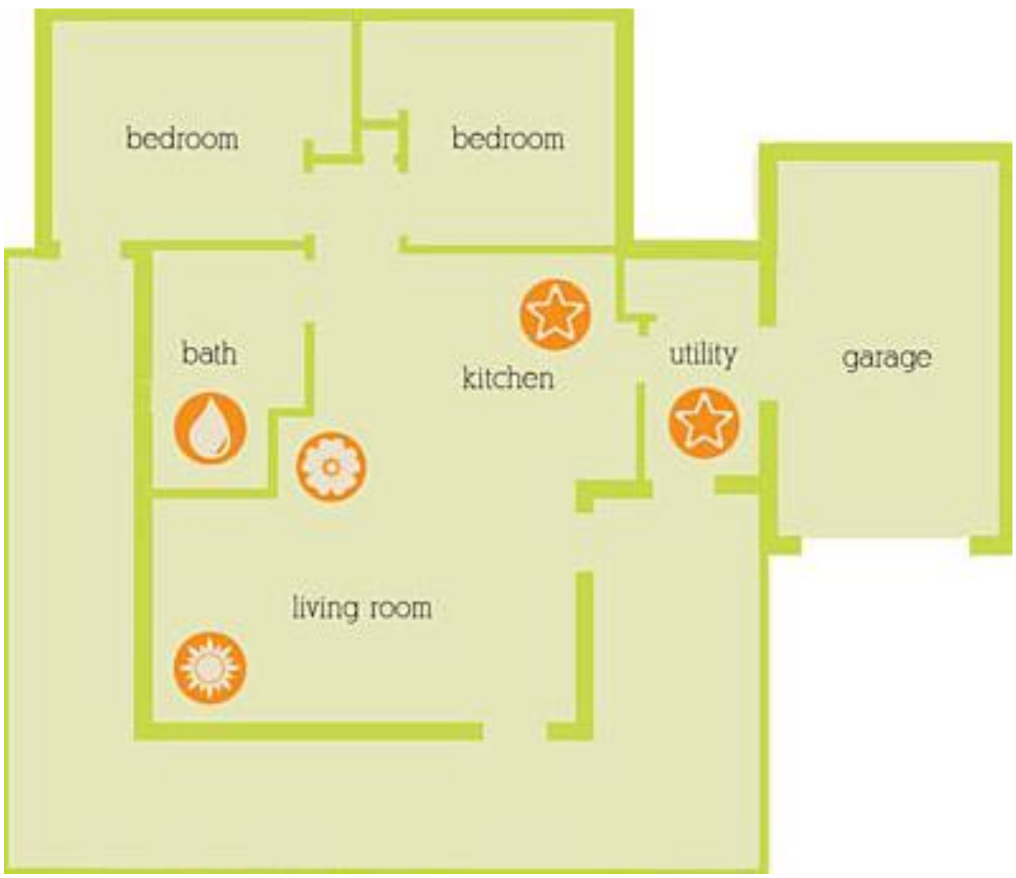

Figure 2: Floor Plan of the INhome

One of the primary energy consuming devices is the electric air source heat pump that provides heating and cooling. This heat pump has two individual compressors that allows for fewer on and off cycles. This not only extends the life of the compressor but also results in a higher efficiency. The heat pump works by using the outdoor air to produce heating and cooling for the INhome, yielding a SEER rating of 19.

The indoor air quality of the INhome is controlled by the energy recovery ventilator (ERV) that removes airborne contaminants and allergens. The ERV provides fresh air inside the home and also pre-conditions the incoming air, reducing the energy used by the HVAC heat pump to condition the air to room temperature.

Four different web-based platforms provide the “smart” features of the INhome. One is an advanced system for monitoring component level electrical consumption of the home. The second system monitors the performance of the solar panels. The third systems provides home security, such as the ability to lock/unlock doors and turn on/off lights remotely using a smart phone app. The final system provides web-based monitoring and control of the HVAC system in the home.

2. EVALUATION

Figure 3 shows the electric energy in the INhome over a three-year period. The data summarizes the electrical consumption consumed by the home (blue) and the solar production of the solar panels (orange) measured in kilowatts per hour (kW-h) for the years 2013, 2014, and 2015. The home is all electric so this summary provides a comprehensive view of total energy consumption. The data was collected using a web-based electricity monitoring system that was attached to the main electric panel and the solar array.

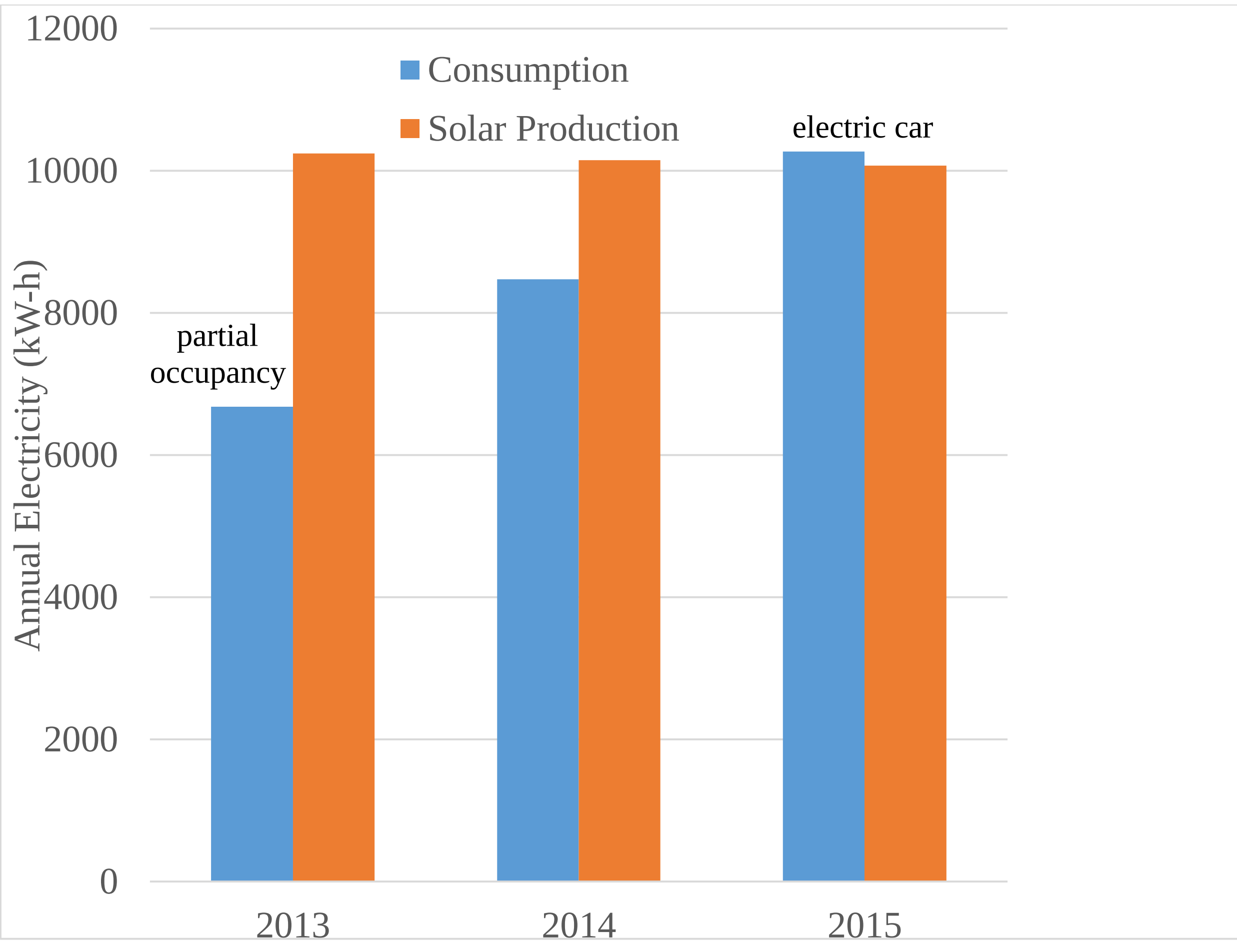

Figure 3: The INhome has been net zero for the past 3 years.

Figure 3 shows that the INhome has been net zero for each of the last three years. The solar production (orange) has been consistent at about 10,000 kWh each year. The production has been surprisingly constant, despite small-scale weather anomalies like the “polar vortex” that covered the INhome’s solar panels with snow for much of January, 2014.

The electrical consumption (blue) has increased in each of the past 3 years. As noted on Figure 3, 2013 was not quite a full year of occupancy. The 2013 energy consumption was low because the homeowners were still moving in. 2014 was a full year of occupancy, but the solar panels still generated approximately 15% more energy than the homeowner actually used. For 2015, the electrical consumption and solar production were nearly equal.

The 2015 match between consumption and production was not an accident, but a smart decision by the homeowner to take full advantage of the electricity being generated by the INhome. The homeowners purchased an electric lawnmower and even an electric car to use all of the solar electricity produced. This is a by-product of the Indiana Utility Regulatory Commission's net metering rules, whereby a homeowner is credited for the solar power they produce but there are no additional benefits for an annual surplus. Thus it is wise to use all of the renewable electricity as it is generated.

Figure 4 shows the individual components of the electrical consumption of the INhome for 2015. The data was taken from the main electric panel by a system that monitors the energy use of each circuit in the house. The five broad categories are HVAC, Kitchen, Laundry, Controls, and Lights & Plugs. The HVAC component includes the electric consumption of the heat pump (outdoors), air handler (indoors), and the ERV system. The kitchen component is the refrigerator, oven, dishwasher, and other devices used for cooking. The laundry component is a washer and dryer. The controls component includes four different types of web-based energy monitoring equipment. The lights & plugs is all the remaining electricity in the home.

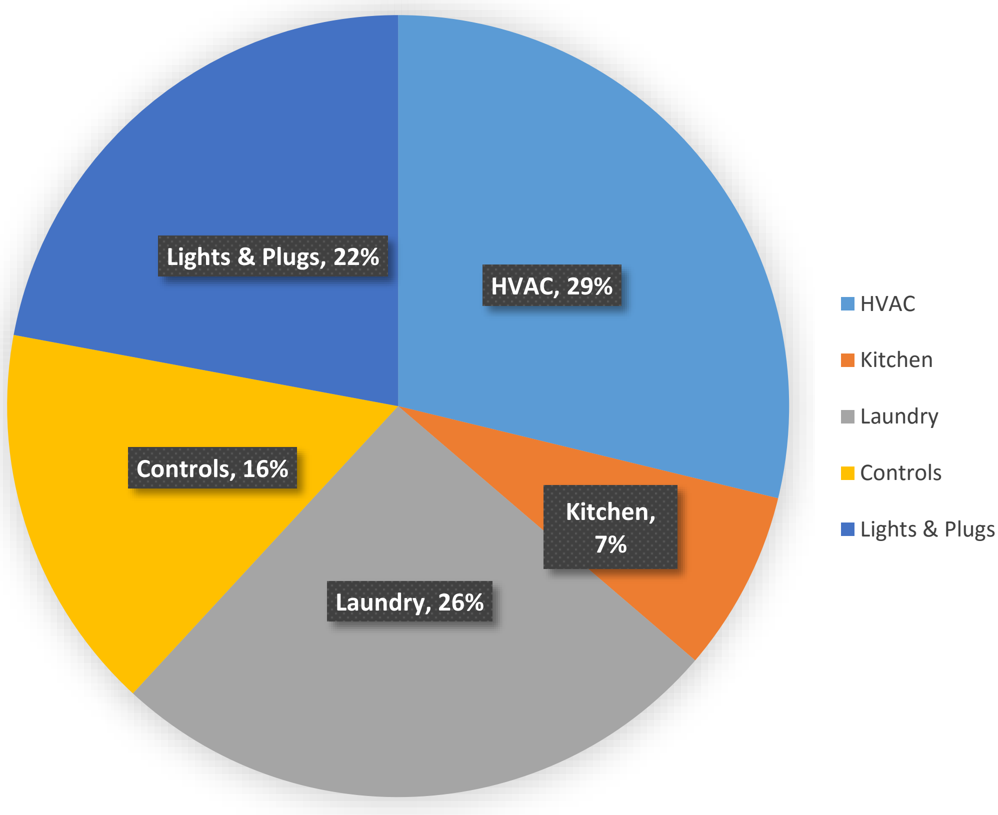

Figure 4: 2015 Electricity Use of the INHome

Figure 4 shows that the HVAC system is the single biggest consumer of energy. That is not surprising due to the sometimes extreme weather conditions of Indiana. The laundry used the 2nd most energy, followed by the lights & plugs. The controls used a surprisingly large amount of energy, but this is there are 4 separate monitoring systems that operate 24 hours a day and 365 days a year. It is also interesting that the kitchen consumes the smallest amount of energy, probably due to the high efficiency appliances used throughout.

Figure 5 is a graph of annual energy consumption and solar panel production for 2015 on a cumulative basis. The vertical axis is a % of annual electricity to provide insight about the interaction between production (blue) and consumption (orange) on a monthly basis. The graph shows that electrical energy is consumed at a steady rate throughout the year. The blue trend line is mostly linear. Most of the electric loads in the INhome are fairly constant. Even the electricity used in space conditioning, heating in the winter and cooling in the summer, is essentially at constant rate.

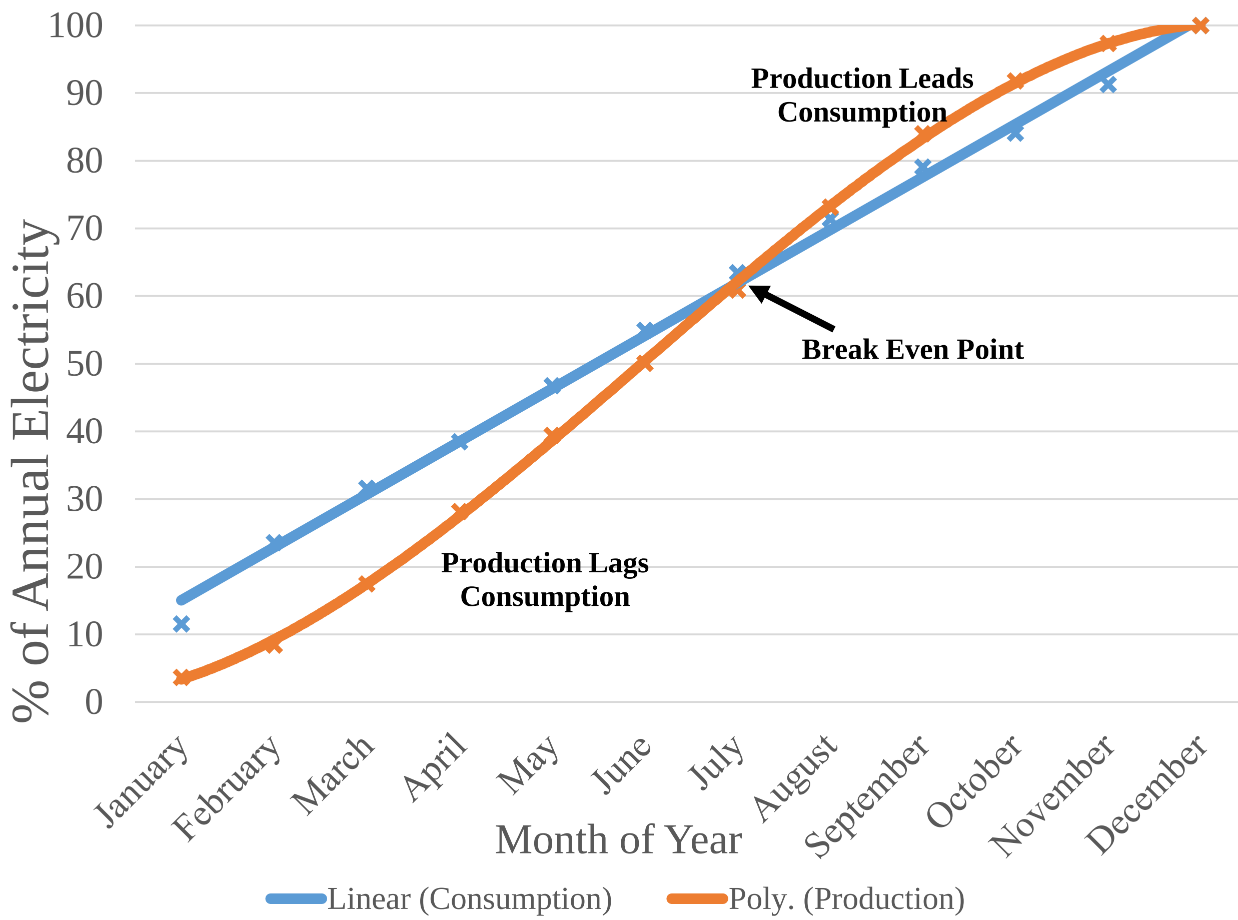

Figure 5: 2015 Annual Energy Consumption vs. Solar Panel Production

Figure 5 shows that energy production by the solar panels (orange) varies over the course of a year. In January when the days are short and snow sometimes covers the panels, solar production lags consumption so some energy is taken from the grid. Solar production starts increasing in March. By the July/August time frame solar production reaches the break-even point where consumption and production are in balance. Solar production leads consumption until December when the days are short and solar energy is at its minimum.

Although it is not clearly visible from Figure 5, a closer inspection of the electricity consumption shows that it does increase slightly for the winter months, January and February. Then as the weather conditions become warmer, the electrical consumption decreases. Electricity use then increases sharply from October onwards, when the weather conditions start to become much colder. The electrical consumption increases primarily due to the heat pump. During the warmer months of summer, the heat pump works best due to using the warm air from outside. Though, during the winter there is very little heat that can be used by the heat pump. Thus, the heat pump then relies on electricity to heat and cool the INhome during the colder months. As a result, more electricity is consumed during these colder months.

Overall, Figure 5 shows that the electrical consumption and solar panel production both offset one another over the course of a year. When solar panel production increases the electrical consumption decreases and vice versa. The overall result is a net-zero energy home.

3. HOMEOWNER SURVEY

An informal survey was given to the current homeowners of the INhome to gage their overall satisfaction after 3 years of occupancy. The 10 question survey about the installation of solar panels, energy efficient appliances, and overall comfort of the home was submitted to the homeowners before a short interview at their home. This non-scientific survey revealed that overall the homeowners very much enjoy living in the home. In regards to the solar photovoltaic panels, the homeowners recognize that these panels produce more power than what the home is using. As a result of this, the only energy cost the homeowners pay is the service fee to the electric utility for being connected to the grid. The homeowners are thrilled by this and have even recommended the installation of solar photovoltaic panels to several others.

The energy efficient appliances were also highly recommended. One of the more unique energy efficient appliances is an induction cooktop that was well received by the homeowners, because it is both aesthetically pleasing and performs very well. The only drawback was that the induction cooktop requires certain types of cookware that only a few companies sell. The air source heat pump for heating and cooling was another appliance that was rated highly by the homeowners because it provides consistent temperature and humidity control inside the home. The ERV system was very well received in terms of reliability, functionality, and practicality for providing adequate fresh air and controlling humidity levels in the INhome. It was consistent in automatically turning on and off when needed, and was described as being nearly flawless in its functionality.

The overall comfort of the INhome was described by the homeowners as a “delight to live in”. They cited the overall layout, architecture, and outside wraparound deck as a few of the most enjoyable features. The open-concept layout of the home in particular was a favorite feature, in that it manages to let in large amounts of natural light. This was primarily accomplished by the large south-facing triple-pane and clerestory windows. The triple-pane windows help keep the home from any heat losses and the clerestory windows provide additional fresh air into the home when open.

There was one interesting development in terms of the smart home controls that provided detailed energy monitoring and smart phone apps for door locks and lights. Although they had a high “wow” factor to the new homeowner, these features were not really used on a day to day basis. As years passed, this monitoring equipment became more of a nuisance because it took up space and used un-necessary energy. That is why these smart monitoring components were ultimately removed. The homeowners placed a higher value on simplicity than high tech gadgets.

4. CONCLUSIONS

The INhome achieved one of its main design goals by being consistently net zero from 2013 to 2015. The first years of occupancy showed that the homeowners were not utilizing all the energy produced by the solar panels, resulting in excess energy being delivered to the electric grid. However, electricity consumption has increased as the homeowners made a conscious decision to use more “free” electricity. By 2015, the production and consumption levels were nearly equal. In addition, it was also found that the HVAC appliances used the most energy every year, due in part to the fluctuating weather conditions. The overall functionality and livability of the INhome was described by the homeowner as being flawless and very enjoyable to live in and that the INhome is a perfectly designed home to showcase energy efficiency and solar energy of today.

NOMENCLATURE

INhome	Indiana home
HVAC	heating, ventilating, and air conditioning
ERV	energy recovery ventilator

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