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Residential energy monitoring: Missouri S&T Solar Village development

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RESIDENTIAL ENERGY MONITORING:
MISSOURI S&T SOLAR VILLAGE DEVELOPMENT

by

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ABSTRACT

As energy costs are rising, public and private sector groups are searching for improved energy efficiency technology. Research tools for predicting residential energy usage are lagging behind commercial developments. Missouri S&T has a unique and strong opportunity to strengthen its involvement in the development of residential energy research and knowledge. The S&T Solar Village, a collection of homes designed for energy efficiency and renewable energy, is poised to support this research. This thesis develops a design for residential energy evaluation and data collection of the four solar homes in the Village. The energy evaluation system identifies over 300 sensors and equipment to monitor and analyze energy production and consumption. The sensor suite is designed to collect data on weather, energy production, energy consumption, and resource utilization for a full building envelope analysis. This thesis also reviews the additional work of installation and data collected from the AC electric sensor set and a designed electricity information feedback interface for the Solar Village. Finally, a discussion of energy research opportunities made possible by the sensor suite is presented.

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NOMENCLATURE

Symbol	Description
$\dot{V}$	Volumetric Flow Rate
T_{input}	Temperature of Input Material
T_{output}	Temperature of Output Material
c_p	Specific Heat of Material
ρ	Density of Material
T_{CW}	Temperature of Cold Water
T_{HW}	Temperature of Hot Water

1. PREFACE

This thesis is intended as a report of the research that has been completed and the design behind the evaluation system of S&T's Solar Village. It is also intended to support the development of future research projects that can branch from this attempt of residential building evaluation on the campus of Missouri University of Science and Technology. There are many suggestions and opportunities presented in this research for future work.

2. INTRODUCTION

With the average residential cost of energy rising 42% in the last 10 years (United States Energy Information Administration, 2010) and the push for consumers to be more environmentally conscious, the need to reduce end-use energy is ever increasing. The Building America program (Building Technologies Program, 2010) from the U.S. Department of Energy has a goal to reduce the average energy use of residential housing by 40% to 100%. According to the Energy Information Administration (EIA) the average energy use for the American household in 2005 was approximately 27,812 kWh per year. (United States Energy Information Administration, 2009) This would mean that the average US household would need to consume less than 16,687 kWh per year to meet that goal. Tools have been developed to assist the user in reducing energy such as more efficient products, feedback systems, and active control systems.

Studies have been carried out to quantify consumers' responses to different avenues of information supplied to the user about their energy consumption, or energy feedback. Indirect feedback studies where the user receives information that has been processed, like in monthly billing, have shown a reduction of 0-10%, direct feedback studies, where the consumer utilizes a display to see the real-time energy consumption, have shown a reduction of 5-15%; and pay-as-you-go systems have shown the largest effect at 10-20% savings. (Darby, 2006)

Missouri University of Science and Technology (Missouri S&T, S&T, or University) has built four homes for the U.S. Department of Energy Solar Decathlon competition. These homes have been designed with energy efficiency in mind and have been placed on campus for student housing. These homes bring a unique opportunity for the University to increase the residential energy research presence. To utilize these homes in research, there has to be a way to measure, report, and evaluate the building's design and the performance. This thesis reports the efforts to design an evaluation system for the Missouri S&T solar village that allows for future research of the following objectives:

- Compare the energy efficiency of the original design of the buildings,
- monitor and compare the energy performance of the buildings amongst themselves and all other buildings, and
- develop a database of information that can be easily used for residential research in building design, system design, and tenant lifestyle.

The current literature of energy evaluation systems and energy management products are first reviewed. Then the Missouri S&T solar village and each house therein are reviewed to explain the target buildings and their attributes and the evaluation system and procedures are selected for use in the solar village. The system is designed for application to the solar village and the sensors and hardware are selected. Additional work is reported in this thesis on the installation of the AC electricity sensor set, selected data is analyzed, and information on a feedback interface for the AC electricity data is discussed. Finally, the author discusses future work and a small sample of research projects possible using the Missouri S&T solar village evaluation system.

3. REVIEW OF LITERATURE

In order to design a system to evaluate the energy use of the solar homes on Missouri S&T's campus, located in the S&T Solar Village, a review of the current research and systems was necessary. There are multiple research projects and products on the market that are intended to measure and evaluate the performance of buildings and the user or tenant impact. These projects can be broken down into three basic groups of (1) design evaluation, (2) performance analysis, and (3) feedback and control.

3.1. DESIGN EVALUATION

The first group is focused on determining the overall efficiency or health of the building through an evaluation process. These typically take into account the design of the building for lower energy consumption with the intention of analyzing the building envelope without the effect of the tenant's habits. This evaluation has two categories: pre-construction and post-construction.

3.1.1. Pre-construction Design Evaluation. The first category does not require a physical structure and can be used to evaluate a design and help to iterate more efficient designs of a building. One tool in this category that is growing in popularity is energy modeling software. There are a vast multitude of software programs on the market developed by many different businesses, universities, labs, and societies, each with a different approach or technique to this modeling. Some of the most widely used programs include Trynsys (Solar Energy Laboratory, 2010), Energy10 (National Renewable Energy Laboratory, 2010), and EnergyPlus (Department of Energy, 2010). The Department of Energy compiled a report of twenty major building energy simulation programs in *Contrasting the Capabilities of Building Energy Performance Simulation Programs.* (Crawley, et al., 2008) This report identified the capabilities of the twenty programs in fourteen comparison areas. As every modeling project has different requirements, the strengths and weaknesses of each program need to be evaluated to determine the most suitable program for that project.

3.1.2 Post-construction Design Evaluation. The second evaluation must be completed after the construction of the building. The approach to assign these ratings includes a full building envelope inspection of building features and systems to measure the efficiency and effectiveness of each of these parts. Tests may include a blower door test, duct leakage test, combustion analysis, or infrared camera to quantify items such as air leakage through the walls from the conditioned space to the exterior of the building, leakage from the HVAC distribution ducts, and the effectiveness of the installed insulation in the walls and ceilings.

The U.S. Department of Energy supports the EnergySmart Home Scale (United States Department of Energy, 2010), also known as the E-Scale, to give a relative comparison of the energy consumption of homes across different climates. This E-scale gives a numerical rating with 100 being the score for the energy performance of a home built to the 2004 IECC building code and 0 being the best rating identifying a net-zero energy home. This scale is highly based upon the HERS Index (Residential Energy Services Network, 2010), developed by the Residential Energy Services Network (RESNET), which is another post-construction rating system.

3.2. PERFORMANCE ANALYSIS

The second group is focused on the measurement and analysis of the building's actual energy performance without necessarily taking into account the original design of the building. This group can be split into two categories of system's efficiency and tenant impact. These systems attempt to measure the effect of the building tenant's habits and the purposing of space on the building's energy consumption. Projects often utilize a performance analysis system specific to their needs and are not easily compared across multiple types of buildings in various climates. For instance, a report titled *Energy analysis of commercial buildings in subtropical climates* (Lam, 2000) calculates the overall thermal transfer value or OTTV to analyze correlations with energy consumption to correspond with governmental requirements.

The National Renewable Energy Lab (NREL) published practices with the intent of standardizing the measurement and performance analysis of buildings by determining performance metrics that have the greatest value for determining energy performance. This research was through the Performance Metrics Research Project (Deru, et al., 2005) for the Department of Energy (DOE) and it produced six technical reports. The technical reports include the following:

- Procedure to Measure Building Energy Performance (Barley, et al., 2005)
- Procedure to Measure and Report the Performance of Photovoltaic Systems (Pless, et al., 2005)
- Procedure to Measure Indoor Lighting Performance (Deru, et al., 2005)
- Procedure to Determine Source Energy and Emission for Energy Use (Deru, et al., 2005)

- Standard Definitions of Building Geometry for Energy Evaluations (Deru, et al., 2005)
- Procedure to Develop a Baseline Simulation Model (Pless, et al., 2005)

The "Procedure for Measuring and Reporting Commercial Building Energy Performance" (Barley, et al., 2005) identifies performance metrics for commercial buildings with the intent of standardizing sensor and information systems in the area of energy consumption, electrical energy demand, and on-site energy production. The "Procedure for Measuring and Reporting the Performance of Photovoltaic Systems in Buildings" (Pless, et al., 2005) identifies metrics for the comparison of performance with the design intent, comparison with other PV systems in buildings, economic analysis of PV systems in buildings, and the establishment of long-term performance records. These two reports are used heavily in this thesis during the selection and design of the evaluation system for the solar village.

3.3. FEEDBACK AND CONTROL

The third group includes systems that are intended to improve energy consumption of the building by affecting the habits of the occupant or the performance of the building. This goal can be reached through feedback avenues and automatic control.

3.3.1. Tenant Feedback. Many research projects have focused on energy-consumption information systems that supply utility use feedback to the homeowner. In most cases, the homeowner will actively reduce the energy and water use to reduce their monthly utility bill. A study in New Jersey (Seligman, et al., 1976) showed a 10.5% average reduction in electricity usage when 15 households were exposed to power consumption feedback. Wood and Newborough (Wood, et al., 2003) examined domestic cooking energy consumption feedback based on periodic paper-based information compared to instantaneous electronic feedback. The periodic feedback improved by an average of 3% and the instantaneous feedback households improved by 10%. A project in Japan in 2000 (Ueno, et al., 2006) measured and displayed end-use electric power and room temperature every 30 minutes. An on-line Energy Consumption Information System (ECOIS) displayed the information to nine residential houses. The display included options to view the day's energy use data, previous data, percentage comparison to previous data, cost associated with energy use, and suggestions for improvement. This project showed an average of 9% reduction in power consumption over a testing period of 40 weekdays.

Large corporations such as Google also see the potential for energy information and feedback systems and have invested to this effect. Google developed the PowerMeter (Google, 2010) which analyzes and displays data on a website that homeowners can log-in to view. This interface will track power over time, predict costs, and allow the user to set an energy savings goal.

3.3.2. Building and Systems Automation. Active home control systems, commonly referred to as home automation, come in many forms from individual systems to products that control multiple systems. A thermostat is one type that monitors temperature at a certain point in the home and will turn on and off cooling, heating, and ventilation systems. There are also lighting control systems that will adjust artificial light intensity and shade control based on information from occupancy sensors and ambient lighting levels. There are many communication protocols on the market, such as X-10

(Yuejun, et al.), Z-wave (Z-Wave Alliance, 2010), and KNX (KNX Association, 2010) that direct the communication between hardware whether it is sensor data or control commands. Most fully encompassing home automation systems are designed and marketed as modular or do-it-yourself systems such as HomeSEER (HomeSeer Technologies LLC, 2010) and Lumina control (Home Automation Incorporated, 2010). These use sensor information to control multiple systems for a more complete home control system. Other measurement and control systems are highly precise and are more commonly used for scientific measurement, research project control, or industrial automation. These systems such as the Campbell Scientific measurement and control family (Campbell Scientific, Incorporated, 2010) and National Instrument's real-time measurement and control family (National Instruments Corporation, 2010) are designed for data acquisition projects and have the ability for control of certain standard devices.

Many research studies have tested the effect of applying an active control system in various ways in order to reduce electricity consumption. A data study at MIT (Ilic, et al., 2002) has identified that a load shift creating a 35% reduction in peak energy demand will effectively reduce the system-wide load in California by 6%. Another research project for load shifting has been implemented on a university building and has decreased the peak load by 15%. (Molina-Garcia, et al., 2007)

3.4. EVALUATION AND CONTROL GROUPS INTERACTION

Although the evaluation and control groups were broken down into three groups, there is often interaction between the groups. For instance some post construction design evaluation modeling programs can be utilized to analyze the energy efficiency based on the habits of the tenant. EnergyPlus (Department of Energy, 2010) has the capability to utilize an occupancy schedule to adjust thermostat settings and internal loads. Figure 3.1 displays the three groups and categories below.

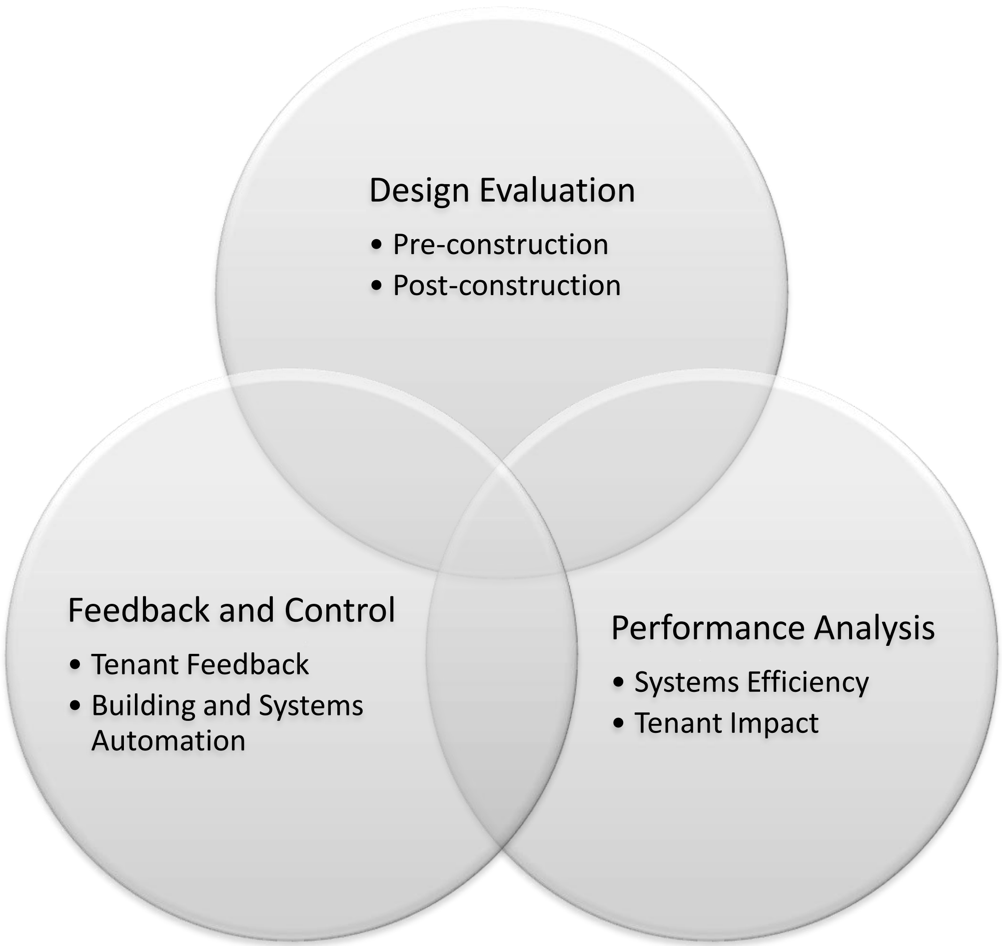


Figure 3.1 Building Evaluation Breakdown

4. SOLAR VILLAGE OVERVIEW

In order to better understand effective systems and processes that will suit the Solar Village and the buildings that will utilize the evaluation system, the layout and design of the village should be understood.

4.1. VILLAGE LAYOUT

The Missouri S&T Solar Village is a plot of land that consists of four solar homes that have been built by the University for the purpose of competing in the U.S. Department of Energy's Solar Decathlon, a collegiate competition to design and build high performing solar houses. These houses are fundamentally different from typical residential houses in that they have been designed for competition with new or different from mainstream building materials and systems. They have also been designed to be modular and have the ability to be constructed and deconstructed in a matter of days. These houses are 1–2 persons, 1-bedroom homes limited to an exterior footprint of 800 square feet. They each reside on an unconditioned basement that contains all the mechanical systems of the house and are serviced only by electricity and water from the city. The houses also all have photovoltaic and solar thermal panels for the production of electricity and hot water respectively. Figure shows a picture of the solar homes and the physical layout of the Solar Village.

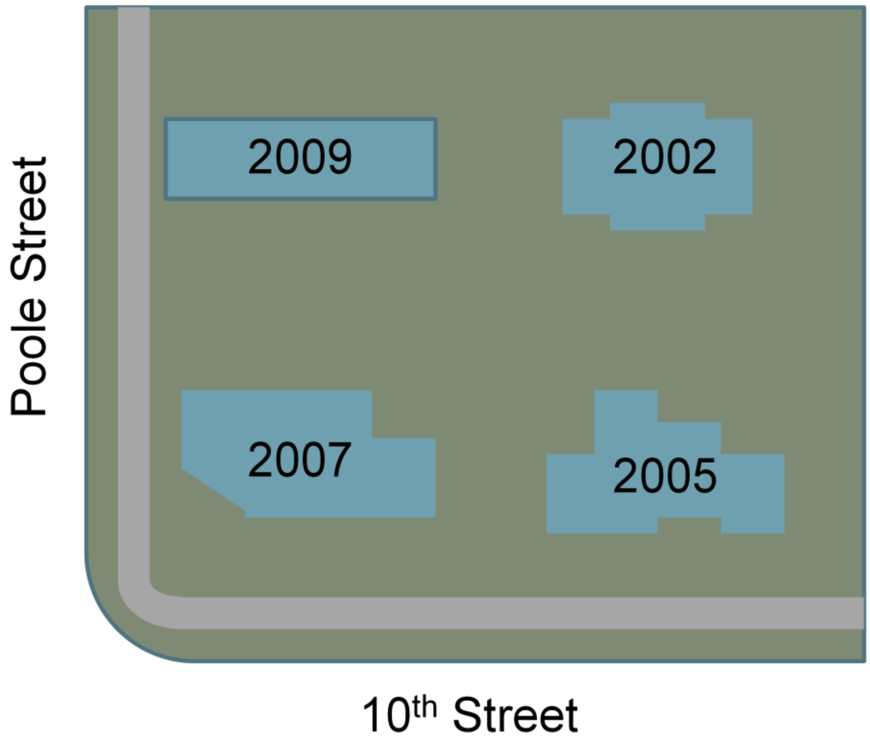


Figure 4.1 Layout of S&T Solar Village

4.2. HOUSE DESIGNS

4.2.1. 2002 Solar House Design. The 2002 house is a steel stud house with rigid foam insulation built on a metal trailer frame. There is an attic space that spans the length of the house and has a six foot tall basement. The house has multi-crystalline photovoltaic panels for electricity production and evacuated tubes for hot water production all located on the roof. This house was designed with a split component heat pump with one indoor dispersion location, but was retrofitted with a central ducted electric furnace for supplemental heat. The design included north and south airlock spaces designed to reduce the amount of conditioned air exchange from inside the home to the outside, but this feature has also been nixed due to the removal of the interior wall and doors of both airlocks. The south airlock has thermal mass to collect heat during the day and supplement heating at night. Figure 4.2 below, shows a picture of the house and the floor plan.

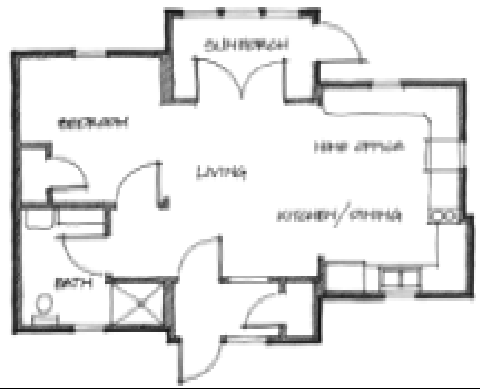
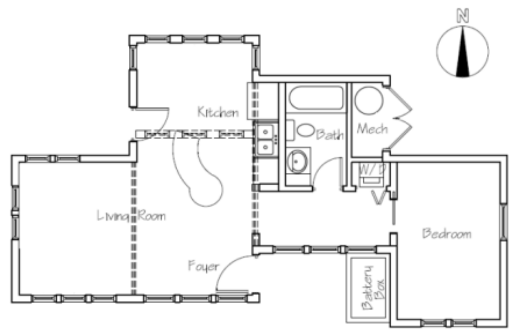
	
2002 House	2002 Floor Plan

Figure 4.2 2002 Solar House and Floor Plan

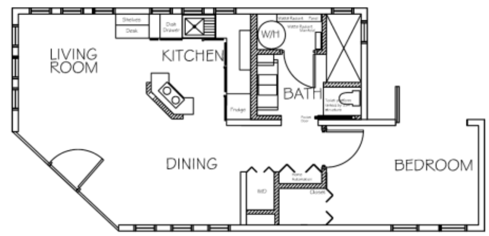
4.2.2. 2005 Solar House Design. The inspiration for the architectural design of this house came strongly from Frank Lloyd Wright's work. The house is constructed of structurally insulated panel (SIP) six inch walls and roof that boost thermal insulation to around R-40. This design also included many windows on all sides of the house and even multiple clerestory windows. Most of the house has vaulted ceilings making for more air volume to condition. The solar photovoltaic and thermal collection systems are a combined hybrid system containing a amorphous film and a flat plate collector for electric and hot water respectively. This house has a large north angled roof that collects electric, but no hot water. The heating system is a hydronic radiant floor and the cooling system is a centralized and ducted compressor and air handler unit. Figure 4.3 below, displays a picture of the house and the floor plan.



2005 House	2005 Floor Plan

Figure 4.3 2005 Solar House and Floor Plan

4.2.3. 2007 Solar House Design. The 2007 house design includes an open kitchen, dining, and living room space with multiple windows. The insulation of the home is built into the six inch SIP walls and roof. The front door was a four pane folding glass wall, but has since been walled in to include a single door. All rooms except for the bathroom are vaulted ceilings. This house is equipped with automated window control connected to a home automation system. Built in speakers also allow audio to be distributed throughout the entire home. The cabinets and flooring are made from eucalyptus wood, which is a greener material than standard wood materials used for those items. The heating for this home is also done by a radiant floor and the cooling is tackled by a ducted compressor and air handler unit. Figure 4.4 below, shows a picture of the house and the floor plan.



2007 House	2007 Floor Plan

Figure 4.4 2007 Solar House and Floor Plan

4.2.4. 2009 Solar House Design. The 2009 house is a rectangular unit made of structurally insulated panels for the structure and insulation and louvers on the exterior to shade the building from summer sun. The entire inside of the building is one large space with a walled in bathroom. Windows are located across the entire north and south sides of the house allowing for a high amount of day lighting. The home is heated by a hydronic radiant floor and is cooled by a centralized compressor and air handler system. Humid air is exhausted from the building through a energy recovery ventilator to reduce heat loss. The home is lighted by mainly LED lighting and has an energy management system that controls the activation of the lighting as well as some appliances. Figure 4.5 displays a picture of the house and the floor plan below.

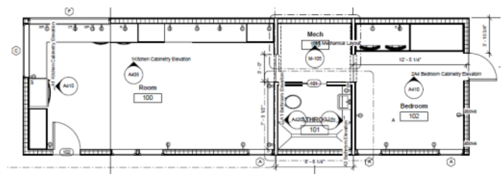
	
2009 House	2009 Floor Plan

Figure 4.5 2009 Solar House and Floor Plan

4.3. COMPARISON OF HOUSES

For a more in-depth comparison of the design of the four houses, a table is provided. This table identifies 24 components or systems within the houses that are useful for the understanding of the building design and performance. Table 4.1 below lists the component or system and describes the type or amount that is located in each house.

Table 4.1 Building Design Comparison

Component or System	**House**			
	2002	**2005**	**2007**	**2009**
Structure	Steel Stud	SIP	SIP	SIP
Wall Insulation	Rigid Foam	Compressed Poly-urethane	Compressed Poly-urethane	Compressed Poly-urethane
Roof Insulation	Fiber-glass	Compressed Poly-urethane	Compressed Poly-urethane	Compressed Poly-urethane
Photovoltaic	Multi-crystalline	Amorphous	Single-crystalline	Multi-crystalline

Table 4.1 Building Design Comparison (cont.)

Component or System	House 2002	House 2005	House 2007	House 2009
Electrical Storage	Lead acid batteries	Lead acid batteries	Lead acid batteries	--
Other B-O-S[1]	Charge Controllers	MPPT[2]	MPPT	MPPT
Grid Interconnect	2-phase	2-phase	2-phase	2-phase
Solar Thermal Component	Evacuated Tubes	Flat plate collector	Evacuated Tubes	Evacuated Tubes
Solar Thermal System	Closed Loop Active Pump	Closed Loop Active Pump	Closed Loop Active Pump	Closed Loop Active Pump
Hot Water Storage	Tank	Tank	Tank	Tank
Water Heating Supplementary	Electric Element	Electric Element	On-demand Heating	On-demand Heating
Heating	Electric furnace	Radiant Floor	Radiant Floor	Radiant Floor
Cooling	Heat Pump	Split Central	Split Central	Split Central
Lighting	CFL	CFL/Halogen	CFL/LED	LED
Refrigerator	Electric	Electric	Electric	Electric
Freezer	Electric	Electric	Electric	Electric
Dishwasher	Drawer	Full unit	Full unit	Full unit
Clothes Washer	All in one	All in one	All in one	Yes
Clothes Dryer				Yes
Microwave	All in one	All in one	All in one	Electric
Oven				Electric
Air Exchange	--	--	--	ERV
Home Automation	--	--	Windows, Lights, Audio	Windows, Lights, Audio, Appliances

[1] B-O-S stands for balance of systems and encompasses all electric components involved in the conversion from DC electric produced by the photovoltaic panels to AC electric consumed by the house and sold to the grid.

[2] MPPT stands for maximum power point trackers and is the component that controls the amperage and voltage between the photovoltaics and inverters.

5. EVALUATION SYSTEM SELECTIONS

This section will discuss the selected evaluation systems for the Solar Village that will satisfy the three stated goals of this project in the areas of design evaluation, performance analysis, and feedback and control.

5.1. DESIGN EVALUATION

Each home in the Solar Village is designed and built by a relatively inexperienced student team with the intent to incorporate new technologies or systems in the home to accommodate the competition. For this reason, the evaluation of the design of the buildings and the comparison of the buildings is significant. It is suggested by this research that each building should undergo the Department of Energy's E-Scale evaluation and be modeled in an energy modeling program. These evaluation programs will help to understand the efficiency of each design.

As stated before, multiple solar houses contain automation systems with the ability to control systems within the house. EnergyPlus energy modeling program has the ability to analyze an automation system by utilizing activation set-points. This ability will increase the accuracy of the model to match the layout and systems of the homes. For this reason EnergyPlus is proposed to evaluate the design of the solar houses.

The modeling of the buildings is outside the scope of this research, but would be a beneficial future research project for the University. The geometry and modeling processes used in the modeling should be designed to be standard throughout all the homes and able to be compared to buildings outside of this research project. The researcher is advised to review NREL's "Procedure for Developing a Baseline

Simulation Model for a Minimally Code Compliant Commercial Building" (Pless, et al., 2005) and "Standard Definitions of Building Geometry for Energy Evaluation Purposes" (Deru, et al., 2005) reports.

5.2. PERFORMANCE ANALYSIS

5.2.1. Data Desired. Energy is most often thought of as strictly electricity, but that is only one part of the whole energy picture. Heat and light are other forms of energy that get produced, transported, and utilized every day. For instance, sunlight is a form of energy that can be harnessed for light or converted to heat or electricity. Understanding all energy and how it is utilized in the home is a gap in most energy monitoring systems. Figure 5.1 below shows a schematic of sources affecting the solar houses. Sunlight, electricity, and ambient temperature are direct energy sources that affect or are utilized in the home, while wind will influence the effect rate of the ambient temperature and water is a source that carries energy in the form of heat that can be utilized in the home.

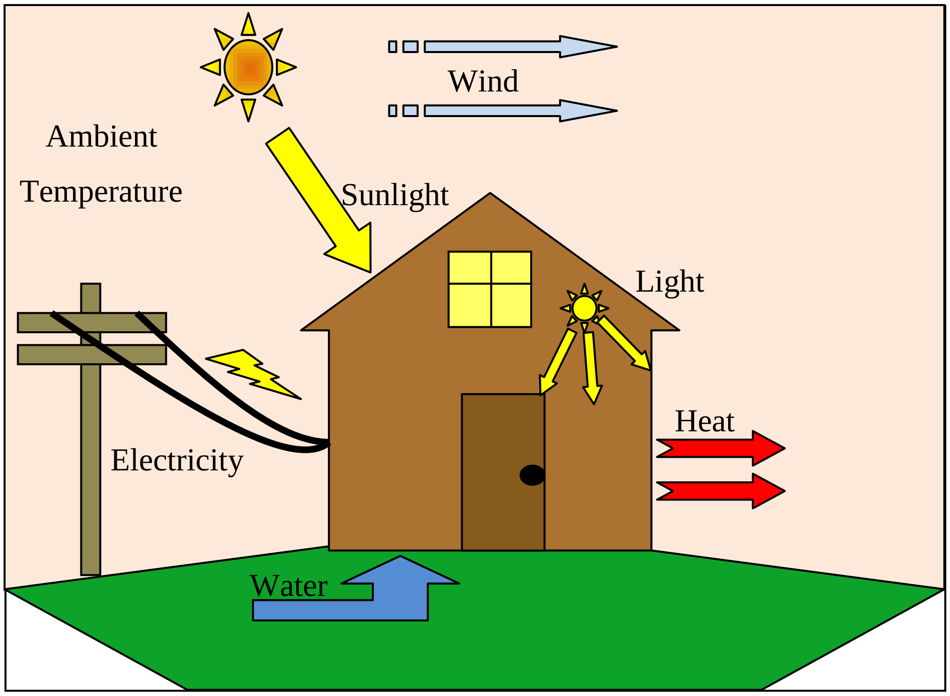


Figure 5.1 High Level Building Energy Schematic

This project is designed to collect performance data on each of the S&T solar houses taking into account the entire building envelope. To attempt to measure all energy sources this evaluation system is designed to include:

- ambient weather conditions (sunlight and wind),
- interior climate conditions,
- electricity consumption, and
- water consumption.

5.2.2. Adaption of NREL Performance Metrics. In the attempt to measure metrics that may be universally used, the "Procedure for Measuring and Reporting Commercial Building Energy Performance" (Barley, et al., 2005) will be used as a basis for the energy monitoring of this project. Considering the building energy performance project was designed for commercial buildings, some metrics and data collection strategies will be adapted where necessary to better fit a residential application.

The monitoring project at S&T will use the tier 2 procedure outlined in NREL's paper to gather a more in depth look at the energy usage in the homes. NREL suggests to use 15- and 60-minute data for energy performance collection, but a residential home uses only a fraction of the energy of a commercial building and at smaller intervals, therefore higher resolution data is needed to capture reliable data. The S&T monitoring system will use 5-second and 1-minute data. The metrics that will be adopted with some adjustment for this project include the following:

5.2.2.1. Functional area (FA). The functional area in each house is the conditioned and unconditioned area that is accessible to the resident. The functional area for the experimental homes will only take into account the first floor. The basement area will not be counted as part of the house systems for the purpose of metric calculations and are therefore not counted in the functional area.

5.2.2.2. Photovoltaic energy production ($PVEP$). This is the electrical energy that is produced by the photovoltaic array before any system components. The purpose of the afore mentioned system components will be taken into account in electrical generation system losses since they are used to convert the produced energy to the facilities usable form of alternating current. This metric is measured in DC power and is compared to the available radiation to determine the efficiency of the photovoltaic array.

5.2.2.3. Thermal energy production (TEP). Energy produced by the solar thermal system is included in this metric. This will be measured by what is produced, not what is transferred to the storage tank. The energy will be measured by the increase of temperature across the solar thermal component and the volumetric flow rate of the collection fluid as shown in Equation 1 below. Where $\dot{V}$ is the volumetric flow rate, ρ is the density of the transfer fluid, c_p is the specific heat of the transfer fluid, T_{output} is the temperature of the transfer fluid at the output of the tank heat exchanger, and T_{input} is the temperature of the transfer fluid at the input of the tank heat exchanger.

Equation 1

$$TEP = \int \dot{V} \cdot \rho \cdot c_p \cdot \left(T_{output} - T_{input}\right) dt$$

5.2.2.4. Electrical generation system losses ($EGSL$). These losses are present in the inverters, charge controllers, and any other components necessary to change the produced electricity to the facility's usable form. In the case of the experimental homes, the usable form of electricity is alternating current (AC) and therefore this metric is determined by calculating the difference in the actual AC output of the inverters to the *photovoltaic energy production*. Battery banks used in conjunction with electrical generation systems are not counted in this metric as they are used for storage, not electrical generation. EGSL is referred to in the *building energy use* metric as part of cogeneration losses.

5.2.2.5. Facility energy production (FEP). Total of all energy produced on site including electricity from photovoltaic, wind, geothermal, solar thermal, and any other means minus all energy generation system losses. Since the solar homes in this research only produce energy from photovoltaic and solar thermal systems, the production of these systems will be summed and the electrical generation system losses will be discounted. There are no thermal generation system losses since there is no system components used to convert the energy into a usable form because the energy produced is already in the facility's usable form of hot water. Equation 2

Equation 2

$$FEP = PVEP + TEP - EGSL$$

5.2.2.6. Produced energy storage transfer ($PEST$). This metric identifies the utilization of storage components. Energy transferred to the storage device is positive and summed and energy transferred from a storage device is subtracted. All types of energy are itemized and measured separately. For these houses, the electricity stored in batteries and thermal energy stored in the hot water tank will be measured separately. The electrical energy is calculated directly in the line and the thermal energy is determined from the temperature drop across the hot water tank exchange coils between the solar thermal collector and the tank.

5.2.2.7. Outdoor ambient temperature (OT). This metric is the ambient exterior air temperature. This will be used in other metric calculations, heating degree-days, and cooling degree-days. Only one sensor will be located in the weather station and will be used in the calculations for all experimental houses since they will experience the same outdoor conditions.

5.2.2.8. Indoor zone temperature (IT). The indoor zone temperature is the air temperature inside the house. The solar homes will have multiple sensors and the temperature will be averaged over all sensors for cooling calculations since there is only one cooling zone per house. Individual heating zone temperatures will be used for heating calculations.

5.2.2.9. Cooling energy use (CEU). This metric identifies all energy used for cooling of the home. This includes energy used to run the air conditioning, heat pump in the cooling mode, control of windows if used for the purpose of cooling, or any other item used for the purpose of cooling. All cooling systems in the experimental homes utilize only electrical energy.

5.2.2.10. Heating energy use (HEU). This is the energy used for heating inside the house. This includes the electricity used to run a heat pump during the heating cycle, furnace, and radiant floor electricity and thermal energy. These homes utilize thermal energy and electrical energy for the radiant floor and electrical energy for the furnace and heat pump. All electricity used to cycle the water through the radiant floor is also measured and summed in this metric.

5.2.2.11. HVAC energy use ($HVACEU$). This metric sums the total energy use of HVAC systems including the heating and cooling energy use metrics that have been identified previously. Other systems that will be added to this metric include ventilation components such as energy recovery ventilators (ERV)s and bathroom vent fans.

5.2.2.12. Domestic hot water load ($DHWL$). DHWL quantifies the thermal energy delivered to the domestic hot water distribution system to satisfy the appliances and other items. The equation for this includes the volumetric flow rate ($\dot{V}$), density of water (ρ), specific heat of water (c_p), temperature of the hot water (T_{HW}), and temperature of the cold water (T_{CW}). The cold-water temperature is the temperature of the water supply before the tank or mixing valve and the hot water temperature is measured after the domestic hot water mixing valve. The volumetric flow rate includes all water supplied to the domestic water heating system. The equation for this metric is shown below in Equation 3.

Equation 3

$$DHWLoad = \int \dot{V} \cdot \rho \cdot c_p \cdot (T_{HW} - T_{CW})\, dt$$

5.2.2.13. Domestic hot water energy use ($DHWEU$). This metric measures the energy used to heat water that is used for any use other than HVAC purposes. This includes the energy consumed to heat the water used for appliances and used at faucets. Energy used for solar thermal collection or any other system to heat water and which is applied to domestic hot water is measured and summed. For the case of the houses in this project, the energy used by the solar thermal system may be used in either the radiant floor heating system or for domestic hot water. The energy used for heating will be calculated and removed by identifying the percentage of hot water applied to the radiant floor versus the domestic hot water. This same percentage will be subtracted from the energy used to produce the hot water.

5.2.2.14. Domestic hot water system efficiency ($DHWSE$). This metric calculates the efficiency of the hot water system to produce hot water for use domestically. This will take into account heat losses in pipes and inefficiencies in the system components such as the heat exchangers and standby tank heat losses. Equation 4 is shown below.

Equation 4

$$DHWSE = \frac{DHWL}{DHWEU}$$

5.2.2.15. Installed lighting energy use ($ILEU$). The electrical energy used for all indoor permanent lights in the house. This does not include lights that have been plugged into outlets for additional lighting. This will be measured from each lighting circuit in the breaker box and adjusting for any non-lighting appliances on those circuits.

5.2.2.16. Other lighting energy use ($OLEU$). This includes lighting that has been plugged into outlets, façade lighting, and any other lighting that is not permanently installed in the building. Lights that are plugged into outlets will be difficult for this metric, but will be estimated by a predetermination of floor lights and load analysis of the outlet circuits.

5.2.2.17. Building lighting energy use ($BLEU$). This sums all energy used for lighting purposes including the permanently installed indoor lights in the $ILEU$ metric, lights that are plugged in, and exterior lighting that are both measured in the $OLEU$ metric. For this metric, lighting circuits must be measured individually or measured in such a way that other loads can be determined and subtracted.

5.2.2.18. Appliance energy use (AEU). All electrical energy consumed by standard appliances will be measured and totalized for this metric. Standard residential appliances are limited to refrigerators, freezers, dishwashers, clothes washers, clothes dryers, ovens, and cook tops.

5.2.2.19. Other building energy use ($OBEU$). This metric is the energy use not included in other metrics. This includes the consumption of plug loads and other systems that do not fall in another category.

5.2.2.20. Building energy use (BEU). This metric is the sum of all energy consumed by the house. This includes heating, ventilation, air conditioning, building lighting, domestic hot water, appliance, and other building energy use. This metric does not count *electrical generation system losses* or *produced energy storage transfer*. As mentioned previously, the $EGSL$ and $PEST$ devices for these experimental homes are the inverters, charge controllers, battery banks, and the hot water tanks.

5.2.2.21. Building energy use intensity ($BEUI$). This metric puts energy use on a per area scale for comparisons with different size homes. It is calculated by dividing the Building Energy Use by the Functional Area as shown below in Equation 5.

Equation 5

$$BEUI = \frac{BEU}{FA}$$

5.2.2.22. Net facility energy use ($NFEU$). Total facility energy consumed minus the energy production. Since all homes in this case study are purely electrical utility and do not use gas or other fuels, this metric will only have an electrical component and the measurement is simply net A/C electricity from the grid.

5.2.2.23. Net facility electrical demand ($NFED$). NFED is the peak electrical demand on the electric utility during each month. This is not the peak demand of the facility; it is the maximum that is bought at any one time from the grid.

5.2.2.24. Net facility load factor ($NFLF$). Average utility electrical demand divided by the peak electrical demand. This metric is calculated for each month and year after the reference month or year has passed. This metric identifies the average percentage of maximum demand of the home on the electric utility during the reference period.

5.2.2.25. Building purchased energy cost ($BPEC$). This metric is the total cost of the purchased electricity from the utility company per month. This will be calculated using the total electric delivered from the grid multiplied by the cost per unit of energy. The actual utility bill will be compared to this metric for verification.

5.2.2.26. Building purchased energy cost intensity ($BPECI$). The cost intensity is the total monthly energy bill divided by the functional area (FA). This is to determine the cost of power per square foot of the home and to be compared to homes of different physical sizes. This metric is shown below in Equation 6.

Equation 6

$$BPECI = \frac{BPEC}{FA}$$

5.2.2.27. Net facility purchased energy cost ($NFPEC$). This metric is the dollar amount of the energy cost for purchasing electricity from the grid minus the credit for selling electricity to the grid. The monetary amount will be calculated using utility cost per unit and the collected electricity data. It will also be compared to the cost incurred on the utility bill. Figure 5.2 below shows the relationship between all energy use metrics that were identified above.

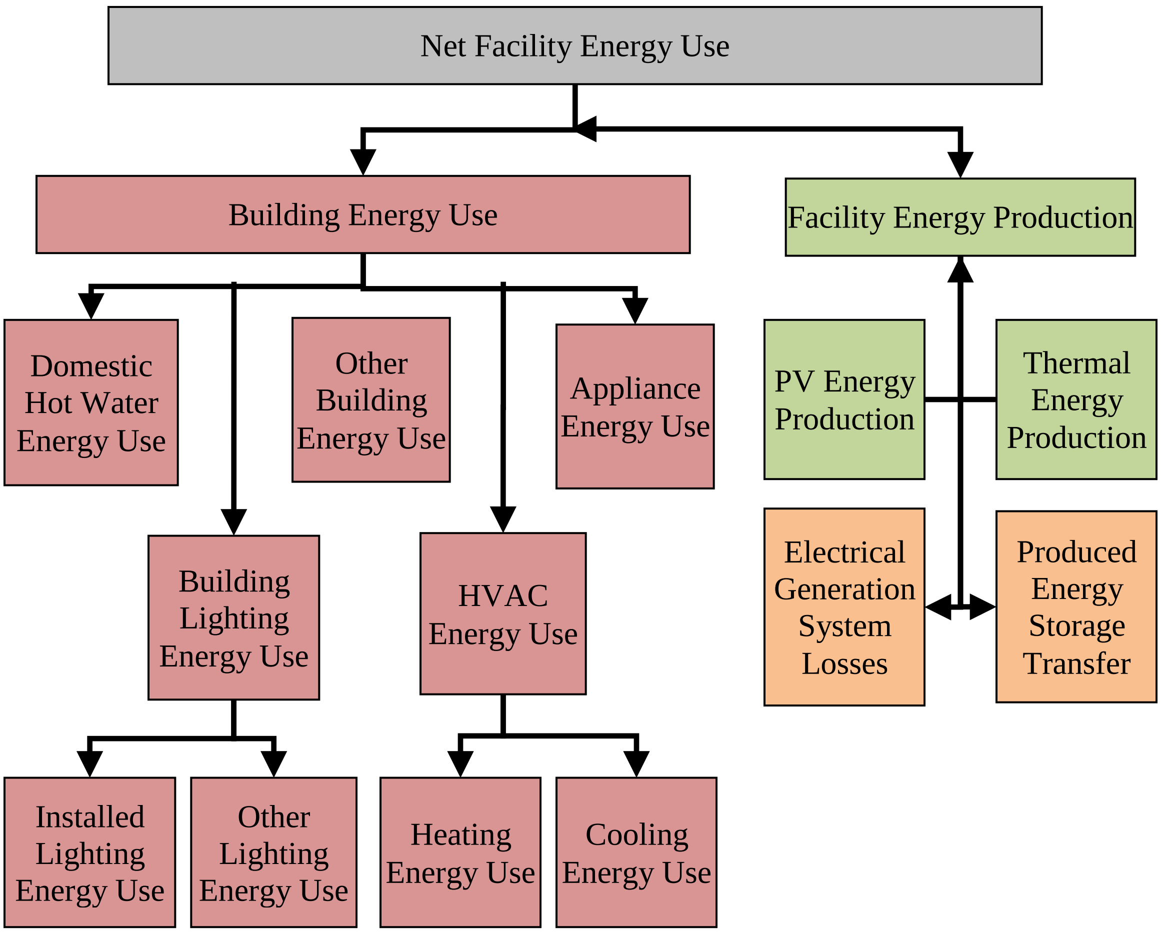


Figure 5.2 Related Energy Performance Metrics

The metrics are summed up to the *Net Facility Energy Use* metric. The directional arrows identify the direction of energy flow. For instance, the *PV and Thermal Energy Production* metrics supply energy to the home while the *Electrical Generation System Losses* has an arrow pointed toward the box and is a consumer of energy. As shown, all *Facility Energy Production* components are not considered as consumers in the *Building Energy Use* metric, their consumption is taken into account in the *Facility Energy Production* group. This diagram has been adapted from NREL's "Procedure for Measuring and Reporting Commercial Building Energy Performance" (Barley, et al., 2005).

5.3. FEEDBACK AND CONTROL

As all the houses in the village have student tenants and two of the houses in the Solar Village contain automation systems, there is great potential for research on affect of feedback systems on tenant lifestyle and affect of control systems on building efficiency. The interface needs to be simple to understand and be easy to correlate energy consumption with specific systems within the house. The performance metrics listed above are directed at researchers and will not be a good selection for a feedback interface. An overall grade for the house with a breakdown of each system within the house and a comparison to previous day's usage is suggested for the feedback system.

6. S&T EVALUATION SYSTEM DESIGN

The installation of an evaluation system for Missouri S&T's Solar Village has the potential to be used for many research projects in building and energy. This is in addition to the consumption evaluation that was discussed in the previous section although some projects may choose to utilize the consumption metrics. The potential areas of research that are being taken into account in the design of this system include research in energy consumption relating to building design, energy consumption related to tenant lifestyle, and energy consumption related to weather or climate. This data must be accurate and precise enough for the use in scientific research. This will also require the hardware and sensors selected to be fully calibrated.

6.1. SYSTEM ARCHITECTURE

In modeling the entire building envelope and to measure the previously mentioned list of metrics a sensor and data logger network is partially installed in all three of the four houses of the Solar Village. The sensors identified and used in this research are highly accurate and precise for scientific measurement. The sensors and system are also to be calibrated on-site to verify the validity of the data collected. The data logger is connected to the University network, which allows the data to be transferred and stored in a database. The web server displays the data from the database and any data can be exported to a program for analysis. The sensor system architecture is visually represented in Figure 6.1 below.

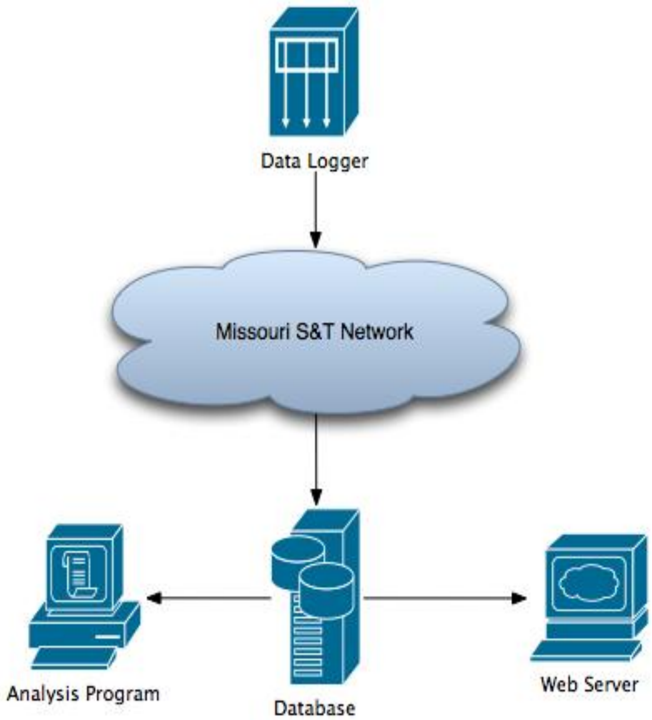


Figure 6.1 System Architecture

6.2. PHOTOVOLTAIC MEASUREMENT

Following the "Procedure for Measuring and Reporting the Performance of Photovoltaic Systems in Buildings" (Pless, et al., 2005) published by NREL, there are six sensors that will be used for the measurement and performance analysis of the photovoltaic system.

First, a pyranometer is placed on the array to measure the incident solar radiation on the surface of the array. In the case of the S&T performance project, there are 4 houses with seven different angles of the photovoltaic and solar thermal arrays. To simplify monitoring and to be more versatile, the pyranometers will not be attached to each house. Instead a group of four sensors will be located in a weather station at horizontal, vertical, and 45 degree angle all facing south with a north facing sensor in the plane of the north facing array on the 2005 house. In this arrangement the incident radiation upon any plane can be interpolated with reasonable accuracy. Figure 6.2 shows a diagram of the aforementioned pyranometer array.

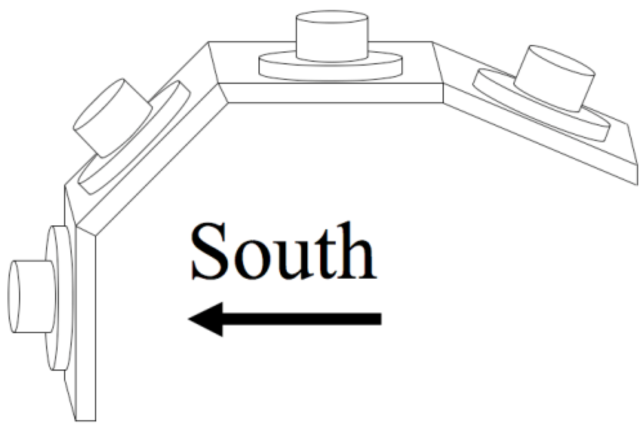


Figure 6.2 Pyranometer Array

To follow the NREL procedures, there are 24 AC electrical power sensors that will measure data in each house. Two sensors measure the bi-directional current of an inverter. They will be located between the inverters and breaker panel and are shown as sensor numbers 1 & 2 in Figure 6.3 titled electrical sensor locations. Utility grid measurements require two sensors as well and are located between the grid and breaker panel (sensor numbers 3&4). House loads will be measured in the building's breaker panel on each circuit to be tracked. This measurement is shown as sensor 5 in the figure. DC power sensors will be located between the inverters and DC bus (7), PV panels and charge controllers (8), charge controllers and DC bus (9), and batteries and DC bus (10&11). Other electrical sensors that are not shown will be located in the breaker panel to measure individual loads of appliances, lighting, and other equipment. These sensors will be placed on the circuit for those particular loads. Care must be taken to only combine circuits of the same phase otherwise the measurement will be affected by the difference in phase of the circuits. All discussed sensor locations are shown in Figure 6.3 as a visual representation as they relate to the electrical equipment.

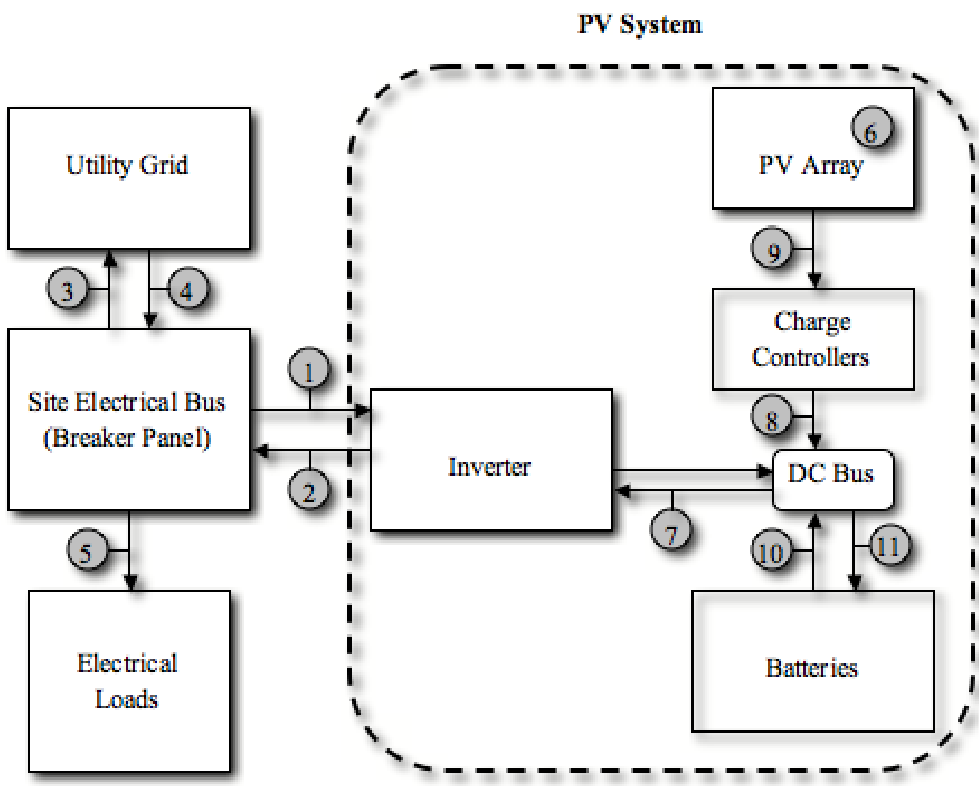


Figure 6.3 Electrical Sensor Locations

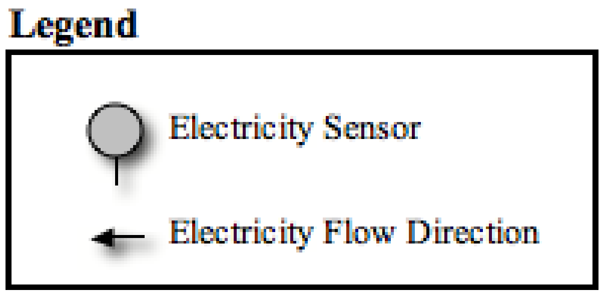


Figure 6.3 Electrical Sensor Locations (cont.)

The metric of the data that is collected from each sensor is listed in Table 6.1. Sensors that will collect data to calculate the NREL performance metrics are sensors 1 through 6 and sensors 7 through 11 are additional research sensors that have been added for additional research and efficiency calculations. The photovoltaic system is considered to be the PV array and balance of systems components. The balance of system (BOS) components includes the inverter, batteries, and charge controllers.

Table 6.1 Electrical Sensor Descriptions

Sensor #	Sensor Measurement Description
1	PV System Standby Use
2	Total PV System AC Production
3	Total Electric Delivered To the Utility
4	Total Electric Consumed From the Utility
5	Total Facility Electricity Use
6	Incident Solar Radiation
7	Inverter DC Power
8	PV Array Production after Charge Controllers
9	PV Array Production
10	Battery Bank Output
11	Battery Bank Input

6.3. HVAC AND HOT WATER MEASUREMENTS

There are four different types of HVAC systems in the houses that will be involved with this project. The 2002 house incorporates a heat pump for heating and cooling plus an electric furnace for supplemental heating during times when the heat pump is inadequate at the ambient temperature. The 2005, 2007, and 2009 houses have a radiant floor system for heating and a condenser unit air conditioner for cooling. Home automation systems in the 2007 and 2009 houses may open windows instead of turning on the air conditioner in certain times. The electricity to operate the windows in these times will be counted toward energy used for cooling.

The hydronic pump board will contain fifteen temperature sensors to measure the energy in three sections of the system. Figure 6.4 is a schematic of the house hot water systems. The first section is the main boiler loop that collects heat from the hot water tank. This will be measured on each side of the storage tank (sensors 12 and 19) to determine the amount of energy that is taken out of the tank and the efficiency with which it is extracted. The second section is the back up tank-less water heater that is used if the storage tank is not hot enough to meet the house demand. Sensors also measure before and after the component (12 and 13) to determine the energy that is added to the system and to compare with the electrical energy used to introduce that thermal energy to the water. The injection loop adds hot water from the boiler loop into the circulating zone loops. The amount of energy being added to the zone loops will be measured (14, 15, and 18) and finally the individual zone loops will be measured (15, 16, and 17) to determine the amount of energy that is within each zone loop. This information will be used to calculate metrics and determine inefficiencies in the system.

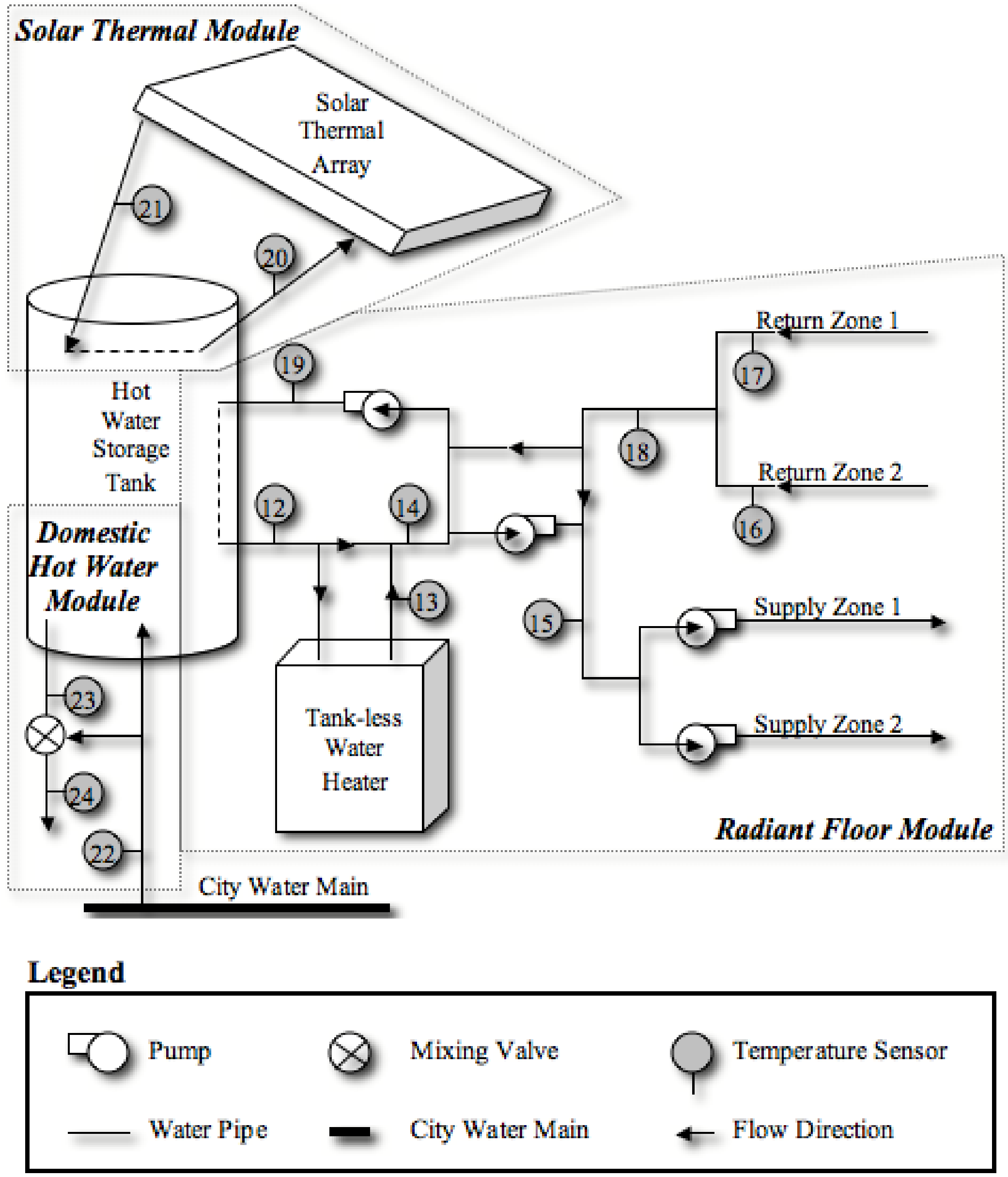


Figure 6.4 Hot Water Systems Temperature Sensor Locations

Table 6.2 below lists the measurement description that corresponds to each numbered sensor in Figure 6.4 and the measurements narrative in the paragraph above.

Table 6.2 Hot Water Systems Sensor Descriptions

Sensor #	Sensor Measurement Description
12	Radiant Floor Tank Output Temperature
13	Tank-less Heater Temperature
14	Primary Loop Supply Temperature
15	Zone Supply Temperature
16	Zone 2 Return Temperature
17	Zone 1 Return Temperature
18	Mixed Return Temperature
19	Radiant Floor Tank Return Temperature
20	Solar Thermal Array Input Temperature
21	Solar Thermal Array Output Temperature
22	City Water Main Supply Temperature
23	Hot Water Tank Supply Temperature
24	Domestic Hot Water Supply Temperature

6.4. SPOT CHECK MEASUREMENTS

Spot checks are one-time measurements that will be used to calculate performance metrics. Table 6.3 below identifies the spot checks that will be completed for each house corresponding to the systems present in that house. These spot checks will measure values that will have negligible change and can reduce the amount of sensor hardware needed. All houses will have a spot check on the volumetric flow of the duct work and will have that measurement applied to the air conditioning metrics, while the 2002 house will have a spot check measurement on the heating duct work as the other houses have radiant floor heating requiring no duct work. The 2009 house requires the measurement of the supply and return ducts of the energy recovery ventilator (ERV) as this system exchanges energy with the outside.

Table 6.3 Spot Checks

Type	Description	Units	House 2002	House 2005	House 2007	House 2009
Volumetric Flow	A/C Supply Air	cfm	x	x	x	x
Volumetric Flow	A/C Return Air	cfm	x	x	x	x
Volumetric Flow	Heating Supply Air	cfm	x			
Volumetric Flow	Heating Return Air	cfm	x			
Volumetric Flow	ERV Outside Supply Air	cfm				x
Volumetric Flow	ERV Outside Exhaust Air	cfm				x

6.5. SENSOR LIST

In order to measure all the metrics to be included in the NREL performance metrics and to design a system that can be used to evaluate the two automation systems, the following sensor list has been compiled. Table 6.4 lists all data that is being collected for each house and relates it to the use and purpose for that information. The model number of the sensor is also listed for reference. This thesis will not go into detail about the reasons for selecting each specific model of sensor.

The first five sensors listed in the table span across all houses. These sensors measure weather data for the entire village and can be applied or compared to data of any house and therefore do not need to be measure at each house.

Table 6.4 Sensor List

Type	Description	Manufacturer and Model Number	Units	Quantity			
				2002	2005	2007	2009
Temperature	Outside air temperature	Vaisala HMP50	°F	1			
Humidity	Outside relative humidity	Vaisala HMP50	%RH	1			
Radiation	Solar radiation	Li-Cor LI-200SZ-50	W/m^2	4			
Speed	Wind speed	R.M. Young 03001	mph	1			
Direction	Wind direction	R.M. Young 03001	degrees	1			
AC Energy	Bi-directional grid interconnect	Continental Control Systems WNB-3Y-208-P	Wh	1	1	1	1
AC Energy	Bi-directional inverter production	Continental Control Systems WNB-3Y-208-P	Wh	2	2	2	2
AC Energy	240 V branch circuits consumption	Continental Control Systems WNB-3Y-208-P3	Wh	4	4	4	4
AC Energy	120 V branch circuits consumption	Continental Control Systems WNB-3Y-208-P3	Wh	16	16	16	16
DC Voltage	Photovoltaic array production	To be determined	V	3	4	4	4
DC Voltage	DC bus	To be determined	V	1	1	1	1
DC Current	Photovoltaic array production	To be determined	A	4	4	3	4
DC Current	Charge controller output	To be determined	A	2	4	3	4
DC Current	Battery charging	To be determined	A	2	1	1	1
DC Current	Inverter consumption	To be determined	A	2	2	2	2
Temperature	Conditioned zone air	Vaisala HMP50	°F	3	3	3	3
Temperature	Unconditioned zone air	Vaisala HMP50	°F	2	1	1	1
Temperature	Refrigerator temperature	Omega HSTC-TT-T-24S-72	°F	1	1	1	1
Temperature	Freezer temperature	Omega HSTC-TT-T-24S-72	°F	1	1	1	1
Temperature	Clothes washer	Omega HSTC-TT-T-24S-72	°F	1	1	1	1

Table 6.4 Sensor List (cont.)

Type	Description	Manufacturer and Model Number	Units	Quantity			
				2002	2005	2007	2009
Temperature	Dishwasher	Omega HSTC-TT-T-24S-72	°F	1	1	1	1
Temperature	Cold water main supply	Omega SA1-T-72	°F	1	1	1	1
Temperature	Domestic hot water supply	Omega SA1-T-72	°F	1	1	1	1
Temperature	Radiant floor heating system	Omega SA1-T-72	°F	-	8	8	8
Temperature	Solar thermal collector loop	Omega SA1-T-72	°F	2	2	2	2
Temperature	Hot water storage	To be determined	°F	3	3	3	3
Temperature	Photovoltaic cell temperature	Omega SA1-T-72	°F	4	4	4	4
Humidity	Conditioned zone air	Vaisala HMP50	%RH	3	3	3	3
Humidity	Unconditioned zone air	Vaisala HMP50	%RH	2	1	1	1
Volumetric Flow	Cold water main supply	Omega FTB4607	gallons	1	1	1	1
Volumetric Flow	Domestic hot water supply	Omega FTB4607	gallons	1	1	1	1
Volumetric Flow	Radiant floor heating system	Omega FTB4607	gallons	-	1	1	1
Volumetric Flow	Solar thermal collector loop	Omega FTB4607	gallons	1	1	1	1
Status	Door operation status	To be determined	1/0	2	2	2	2
Status	Window operation status	To be determined	1/0	6	19	12	12
Carbon Dioxide	Indoor carbon dioxide level	To be determined	ppm	1	1	1	1

7. EVALUATION SYSTEM HARDWARE

Previous sections have discussed the design of the evaluation system for the solar village and the adaptation of building metrics to residential metrics specifically for the solar houses. This section will discuss the hardware and set-up selected to measure the designed dataset and will touch on the installation of the system.

The research and review of multiple data collecting systems identified the Campbell Scientific datalogger and control sensors and system for use in the evaluation. This datalogger can handle the high amount of sensors and is designed for high accuracy and precision required in scientific research. This system is also the system of choice for NREL and the Department of Energy for use in the Solar Decathlon competitions for which these houses were designed. The early involvement of NREL in this research project heavily persuaded the selection of the Campbell Scientific product.

The Campbell Scientific CR3000 datalogger is used for the collection of data from all four houses. Two multiplexers are placed in each home to reduce the number of communication wires run between each house through the underground conduit. The multiplexers will transfer data of the thermocouples, DC power shunts, and air temperature and humidity sensors. WattNodes are also present in each house and will calculate and condense three power measurements per unit. Switch closure modules are located in the 2005 house which attach to the flow and WattNode sensors. The multiplexers, switch closure modules, and weather sensors are wired to the datalogger. Table 7.1 below is a list of the hardware quantities required to measure the 355 sensors and Figure 7.1 is a visual layout of the hardware locations and connections with respect to the solar village layout.

Table 7.1 Hardware Quantities

Hardware	**Description**	**House Quantity**			
		2002	**2005**	**2007**	**2009**
CR3000[3]	Datalogger with connections to sensors and peripherals.	1			
AM16/32 Relay Multiplexer[4]	Measures DC current, DC Voltage, thermocouples, and thermister sensors.	1	1	1	1
AM25T Multiplexer[5]	Measures thermocouples.	1	1	1	1
WattNode[6]	Calculates AC power	11	11	12	9
SDM-SW8A Switch Closure Input Module[7]	Measures flow, and power pulses.	15			

[3] The CR3000 is a compact micrologger produced by Campbell Scientific. Product details can be found at www.campbellsci.com/cr3000-micrologger

[4] Product information can be found at www.campbellsci.com/am16-32b

[5] Product information can be found at www.campbellsci.com/am25t

[6] Product information can be found at www.ccontrolsys.com/products/pulse_output.html

[7] Product information can be found at www.campbellsci.com/sdm-sw8a

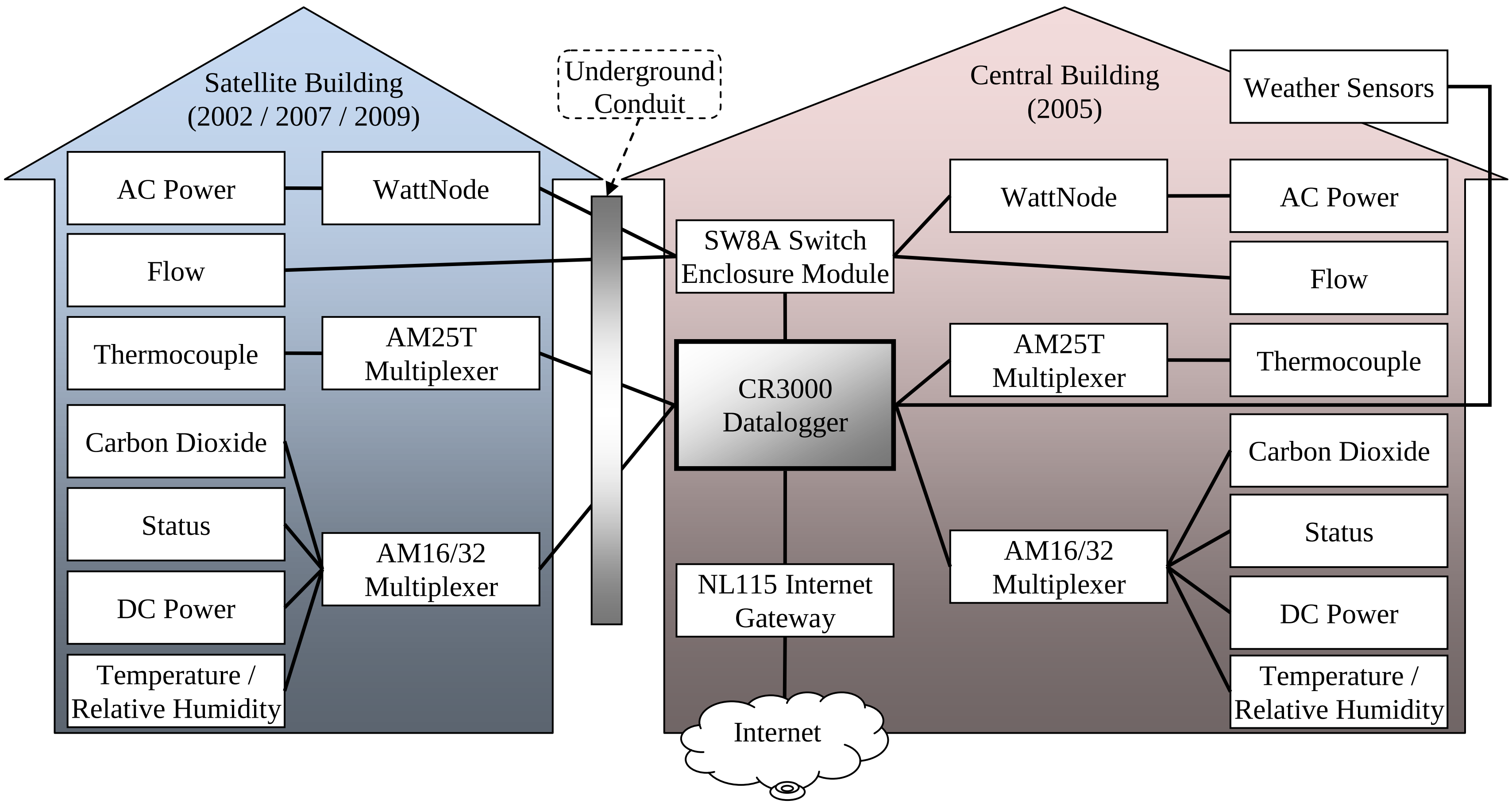


Figure 7.1 Hardware Locations and Connections

8. ADDITIONAL WORK

This section gives information about the continued work after the design of the evaluation system as identified in the objectives of this thesis. Additional work includes the current status of the evaluation system involving the installation of a sensor set, initial gathered data, and development of a feedback interface. This information is being included to strengthen this thesis.

8.1. HARDWARE INSTALLATION

A selected set of the hardware and AC electricity sensors identified in this thesis was procured and installed. Three of the four houses were located in the village at the time of installation activities. This left out the 2009 house from the installation, but has since been reconstructed in the village and is ready for the sensor deployment. A project grant through the National Renewable Energy Lab, titled Solar Decathlon Performance Tracking, is underway at the time of this thesis publication to assist in the continuation of the full evaluation system installation and data gathering.

The datalogger, multiplexers, WattNodes, and the AC power sensors are located in the basements of the houses to allow for inspection and research work to continue without interrupting the tenant. The AC power sensors are located in the breaker boxes at each respective circuit they are measuring and the WattNodes are located next to their respective sensors. Figure 8.1 below shows the standard installation of WattNodes and AC power sensors that are located in the breaker panel and the inverters in each house.

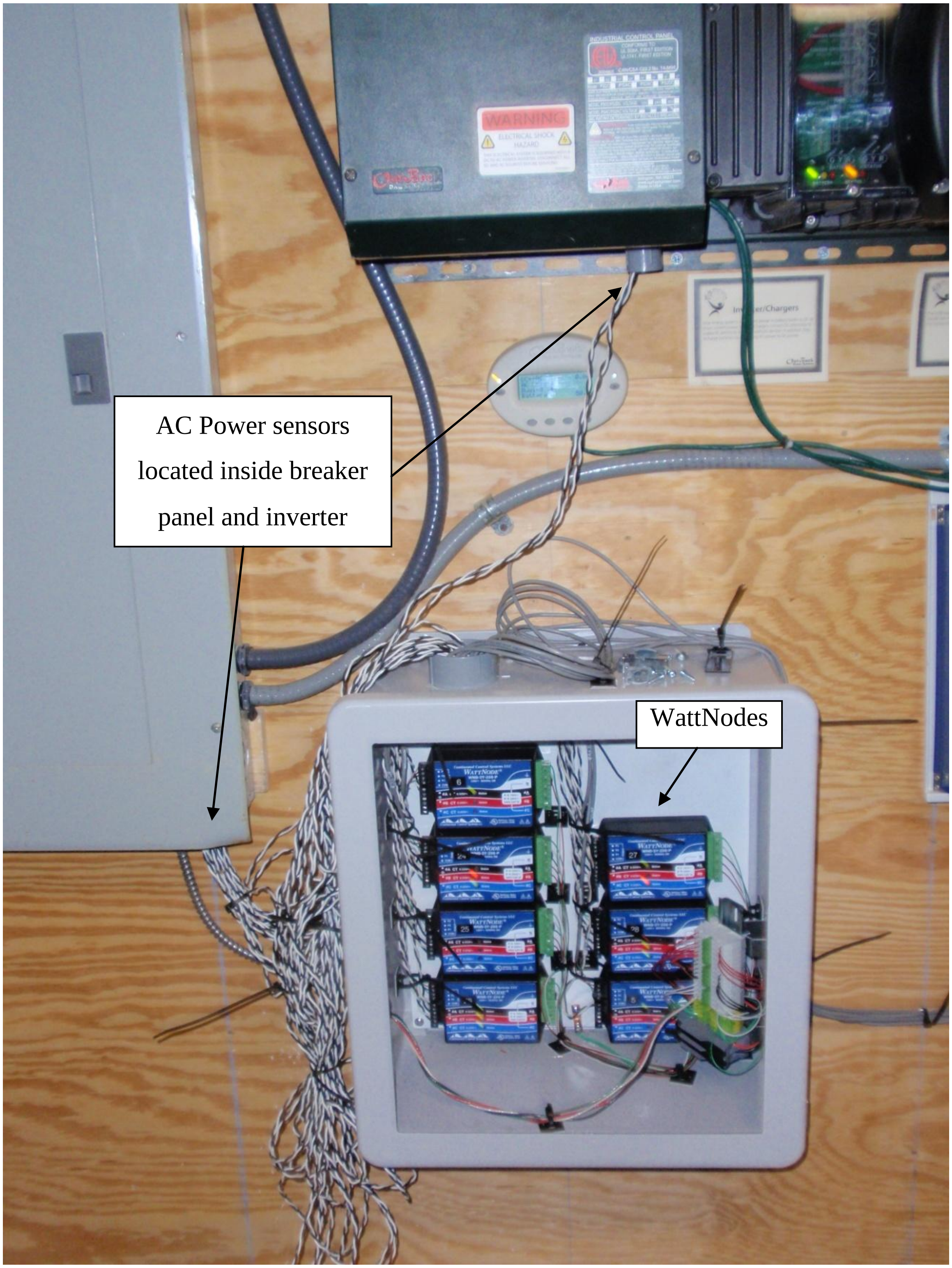


Figure 8.1 AC Power Sensor Set Installation

8.2. RESULTS

8.2.1. Electricity Data. Data has been collected at various times, but has not been continuous as the collection program has been changed multiple times due to program development and testing. March 22nd, 2010 data will be used to analyze the installation of the first set of installed sensors, touch on the metrics described in this thesis, and to assist in the identification of future work.

Figure 8.2 Instant Production and Consumption of Electricity, is a graph of the electric consumption and production of the three homes as measured on the AC circuits from the breaker boxes and the inverters, after the balance of system components, respectively. This graph is a representation of the energy flow on a building level and can identify times of day with the most energy demand. It is helpful to identify peak loads of the buildings and data in this fashion will be used to calculate the load factor metric, NFLF. This data also identifies the peak production of the photovoltaic systems. As seen in the graph, the 2007 house has the largest array, producing almost 5 kW on this day. When compared to the solar radiation and the array size, the efficiency of the system can be calculated. This graph also identifies a shading effect on the 2002 house. The dip in electricity production from a predicted path between starting around 2:30pm shows a reduction from the possible generation. There are an infinite amount of possible analysis situations when data is made available; these are only a few items utilizing just electricity data and the analysis possibilities will increase exponentially with the completion of the full energy data designed in this thesis.

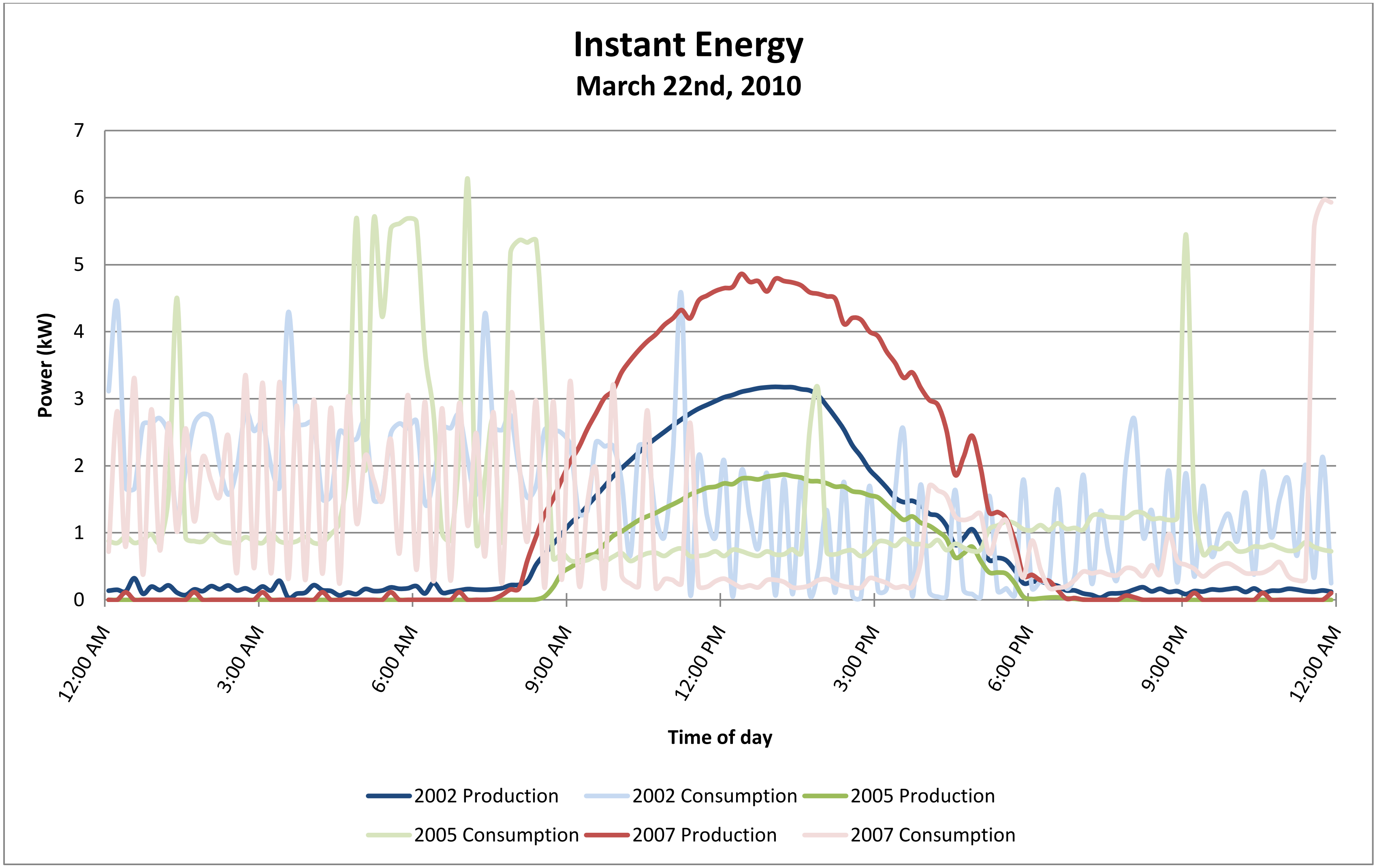


Figure 8.2 Instant Production and Consumption of Electricity

The next graph that is reviewed is the total electrical production and consumption of the three houses. Figure 8.3 below displays the running cumulative of energy on March 22nd, 2010 starting at zero at midnight. This data display is useful to compare the design of the building as compared to a net zero building and is useful to compare to the E-scale rating published by the Department of Energy (United States Department of Energy, 2010). This graph shows that on this day the 2007 house is electrically net negative, meaning it produced more than it consumed. The other two houses are net positive on that day. Although the consumption data is heavily affected by the tenants actions and preferences, this data identifies the 2007 house as using the least amount of energy and the 2002 house as consuming the most amount of energy.

The only metric that can be analyzed with solely the electricity data set is the Net Facility Energy Use (NFEU). As mentioned above, this metric analyzes the net energy entering and leaving the building envelope. Although thermal energy is produced by the solar thermal system, the thermal energy is completely consumed inside the building. Electricity is the only energy that is transported to and from the buildings. This metric is the electricity consumption of the building minus the electricity production, the net of the energy consumption and production in Figure 8.3. This metric can also be calculated by measuring the grid interaction of the houses; that is the amount of energy that is bought and sold from the building.

Figure 8.4 Net Facility Energy Use, overlays both means of calculating the metric. In the case of the 2002 and 2005 houses, the graphs are almost identical, as they should be, but the 2007 data has differences. The NFEU metric calculated directly from the consumption and production of the house show a negative value starting around

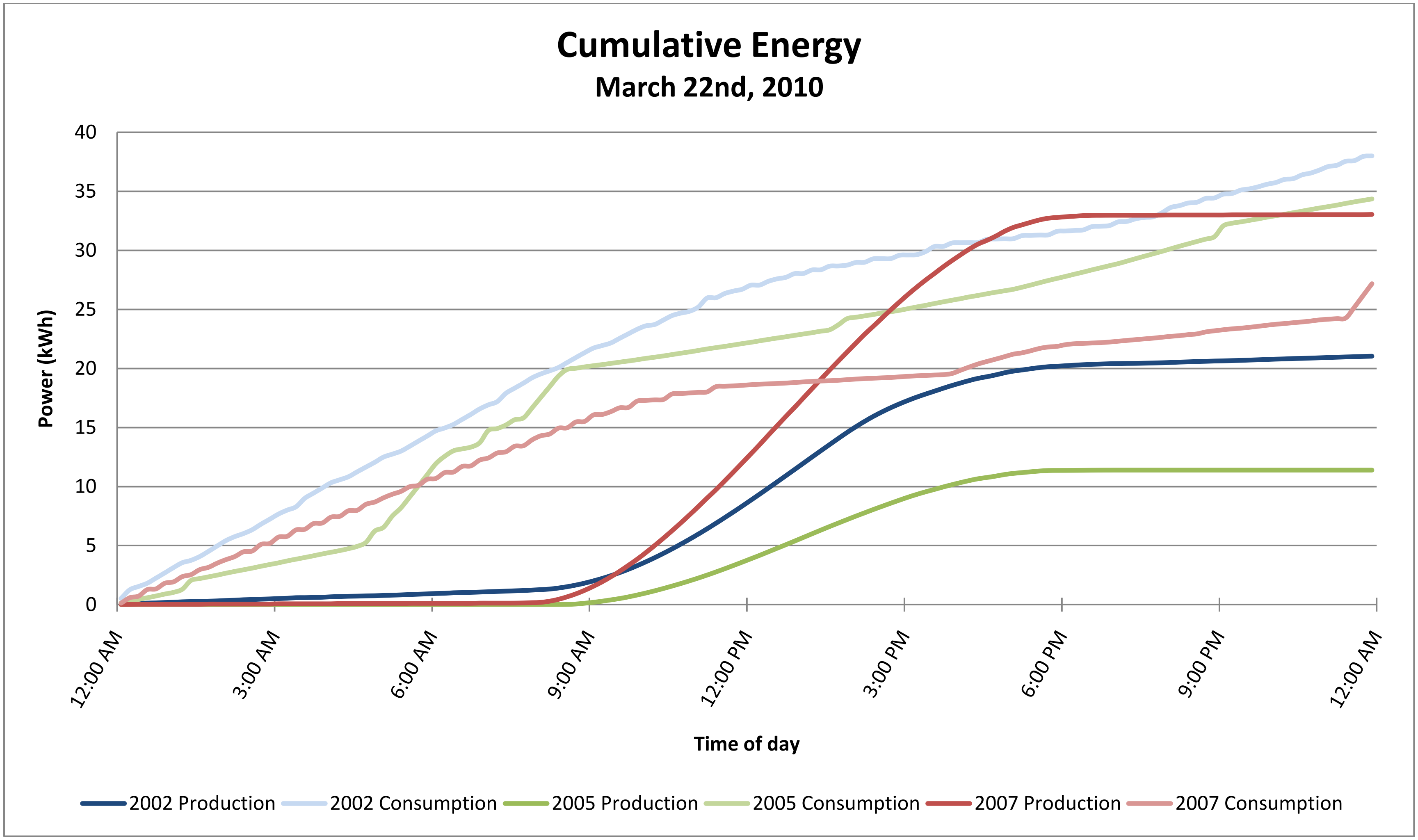


Figure 8.3 Total Production and Consumption of Electricity

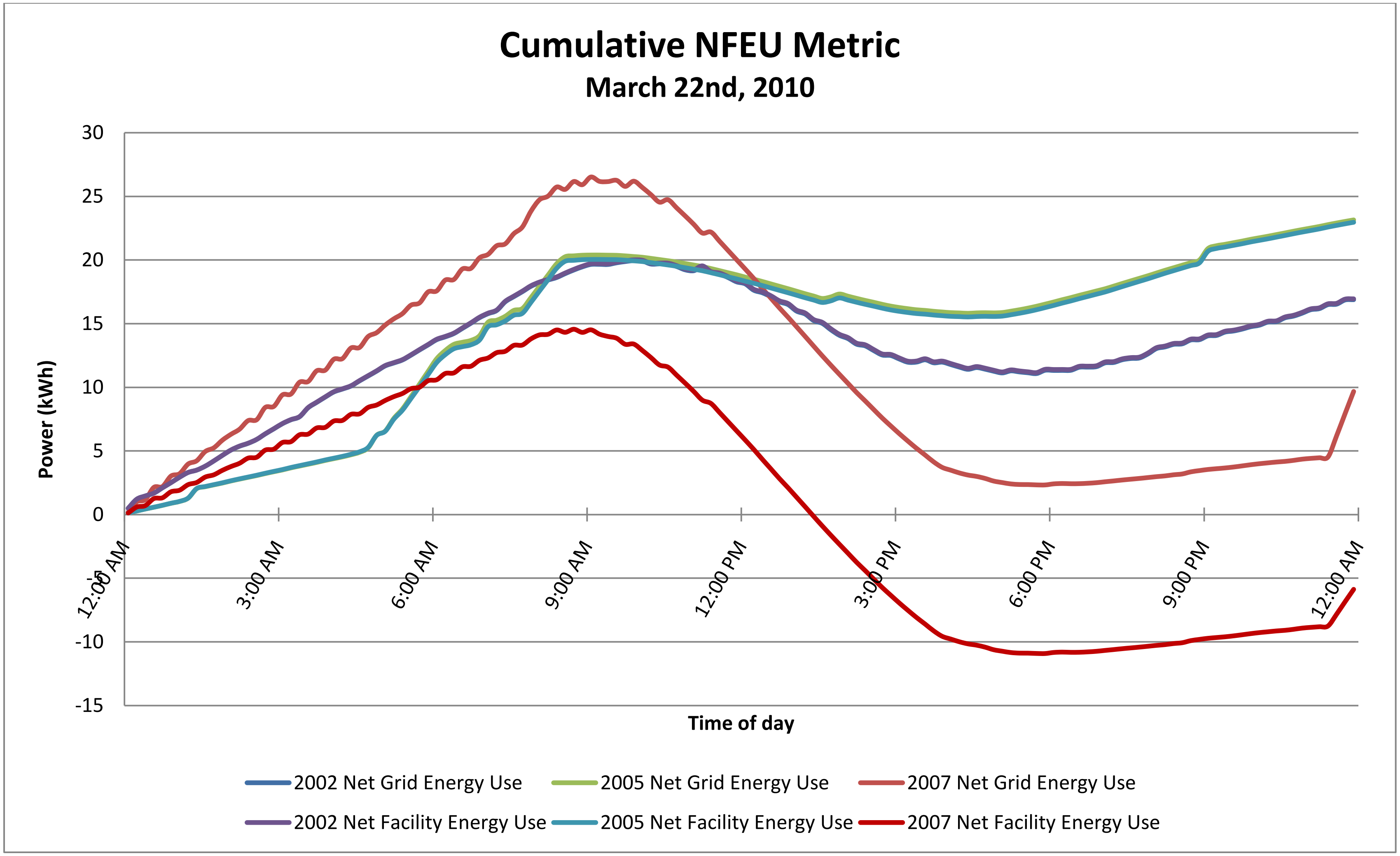


Figure 8.4 Net Facility Energy Use

1:30pm as the previous graphs have indicated, but the metric calculated from the grid interaction data report a positive metric all day. This conflicting data identifies a problem with the design, installation, measurements, calculations, or many other possible scenarios. Verification checks such as this will help to verify the validity of the data and identify other possible problems or improvements in the evaluation system.

8.2.2. Feedback Interface. The data collected by the datalogger is displayed in an energy flow diagram of the electrical energy. It displays the Photovoltaic Energy Production (PVEP) with the Electrical Generation System Losses (EGSL) already removed, Net Facility Energy Use (NFEU), and individual appliance usage with instantaneous power draw and daily cumulative totals. This electricity flow of individual appliances displays the electricity component of a few metrics that have been listed in this thesis and others may be calculated.

Human factors psychology plays an important role in the display of a feedback interface. The display must be intuitive and easy to understand for the general user to gain the most advantage from the interface. For this reason, the display uses arrows and colors to identify the quantity and direction of power flow. Figure 8.5 is a snapshot of the web interface that has been developed. The webpage automatically updates every minute allowing for pseudo real time information. The user can pull up the webpage at anytime and adjust actual energy usage by turning off appliances or systems to stay within the energy production of the PV and in many cases work toward the operation of a net zero energy home. While the user can visualize the major players in the building's energy consumption, this interface supplies numbers that do not mean anything to the average tenant. An enhanced interface would analyze the energy and report a high level grade and give suggestions to assist in the improvement of energy consumption and energy improvements.

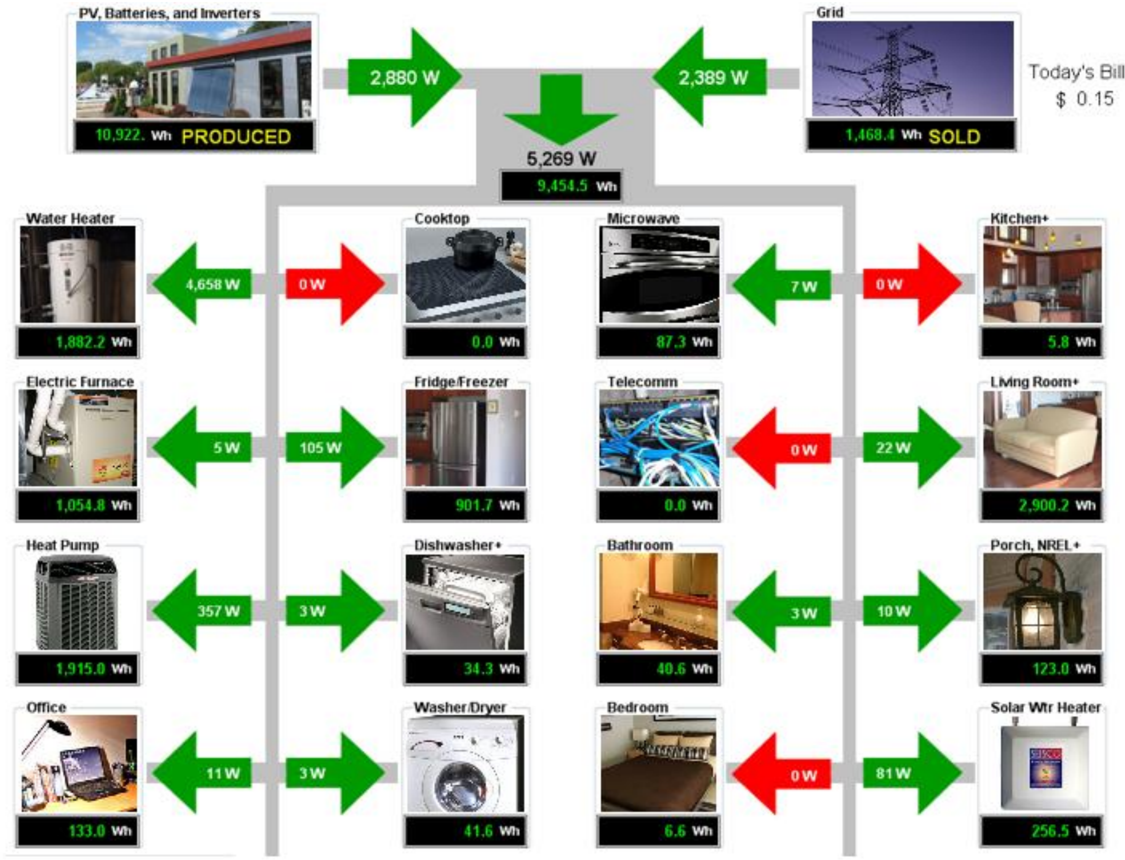


Figure 8.5 Electricity Flow Feedback Interface

9. OVERALL CONTRIBUTION AND FUTURE WORK

9.1. OVERALL CONTRIBUTION

The set up of the energy sensors and design of the evaluation system in the solar village supports the future research of energy management at Missouri S&T. This system design provides the data required to evaluate the monitored homes and compare them on the scale of the full building envelope down to analysis of effects by the tenant. This can first be used to analyze the monitored homes and then further the research and analysis of building energy, specifically the underserved market of residential building energy.

9.2. FUTURE WORK

There is an infinite amount of future research possibilities with the evaluation system in the Missouri S&T solar village. The first and foremost is the complete installation of all the evaluation tools. This includes the installation of the sensors and hardware, calibration of all sensors, set-up of the database and the completion of the collection program. This in itself will be a full research project to test and verify the data. Another project to directly follow up this thesis would be to calculate the metrics listed in this thesis and compare the buildings. This project should use grading systems such as the E-scale to identify the performance of these buildings on a widely used system.

The author would like to have this evaluation system be used to conduct residential energy research and development of energy management systems. Research pertaining to the improvement of feedback displays such as the interface discussed in this thesis. As previous research has shown, information feedback systems alone have the potential to assist the tenant in reducing energy consumption. The next step beyond informational feedback systems is building and systems automation and control. This evaluation system could be used to develop logic for active energy management systems.

As there is an infinite amount of future research possibilities, the development and improvement of all of these systems will be a step toward reaching the energy reduction goal of the Department of Energy and improving building energy science.

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