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Article

Residential Energy Performance Metrics

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Abstract: Techniques for residential energy monitoring are an emerging field that is currently drawing significant attention. This paper is a description of the current efforts to monitor and compare the performance of three solar powered homes built at Missouri University of Science and Technology. The homes are outfitted with an array of sensors and a data logger system to measure and record electricity production, system energy use, internal home temperature and humidity, hot water production, and exterior ambient conditions the houses are experiencing. Data is being collected to measure the performance of the houses, compare to energy modeling programs, design and develop cost effective sensor systems for energy monitoring, and produce a cost effective home control system.

Keywords: simulation and monitoring; energy analysis; solar decathlon; simulation-based control

1. Introduction

The Building America program [1] 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 2001 was approximately 31,854 kWh per year [2]. This would mean that the average US household would need to consume less than 19,112 kWh per year to meet that goal. An energy-monitoring project at Missouri University of Science and Technology (Missouri S&T, S&T, or University) is underway with the goal to identify and develop ways to reduce energy consumption in the residential sector. To accomplish this, a sensor network has been installed in three solar-powered homes that the University has built as part of the Department of Energy's Solar Decathlon competition. The sensor system is key to the start of a residential energy research program to define the building science of whole home energy monitoring. The four major themes of the research include:

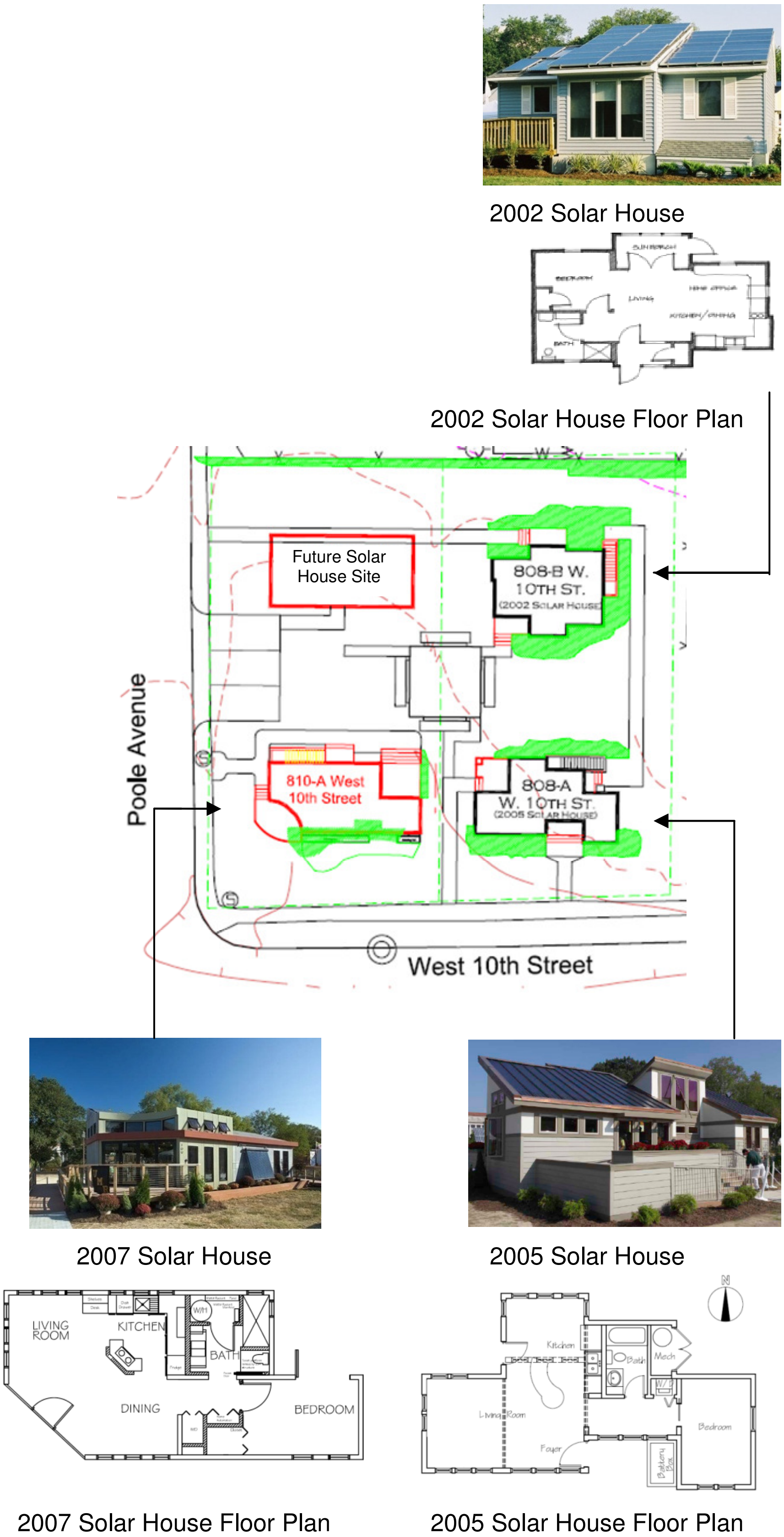
1. Energy efficiency performance data collection of the S&T solar homes;
2. Verification and possible suggestions for improvement of residential design software such as the Sustainable Buildings Industry Council's 'Energy-10' and the U.S. Department of Energy's 'Energy Plus';
3. Design and development of cost effective sensor system for residential energy performance feedback;
4. Cost effective home automation and energy management control system using the sensor system.

This article is focused on the development and plan of the first theme of the research, performance data collection of the S&T solar homes.

1.1. S&T Solar Village

The Missouri S&T Solar Village is a plot of land that consists of three 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 1 shows a picture of the solar homes and the physical layout of the Solar Village.

Figure 1. Layout of the solar village.



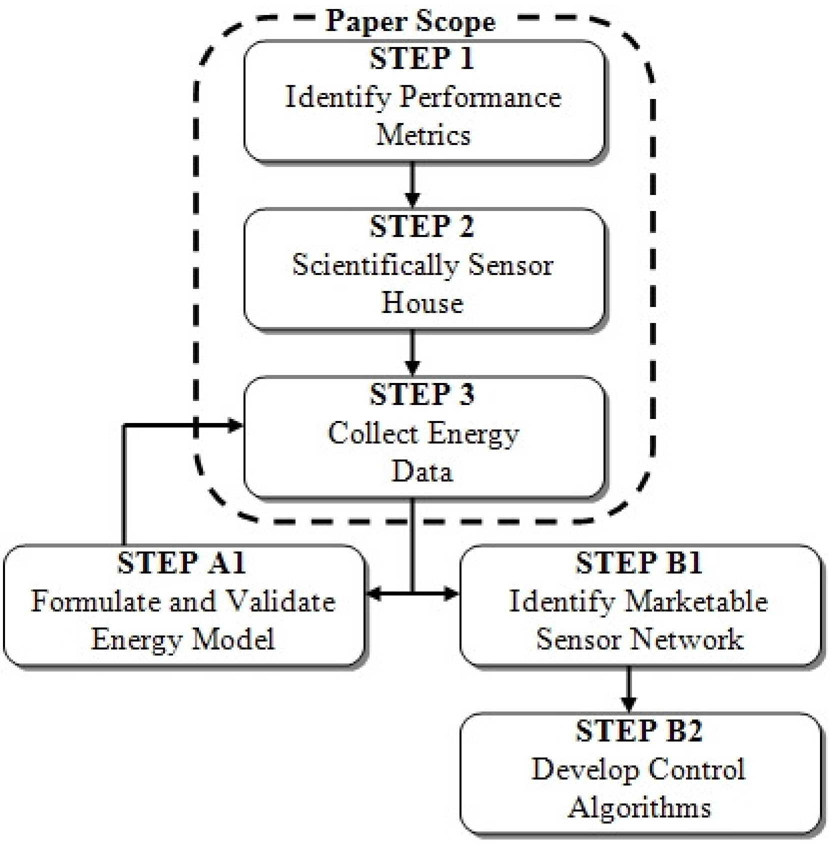
1.2. Research Approach: Model the Entire Building Envelope

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 heat, light, or electricity. Understanding all energy and how it is utilized in the home is a gap in current energy monitoring systems.

The current project is designed to collect performance data on each of the S&T solar houses taking into account the entire building envelope, which includes ambient weather conditions, interior climate condition, electricity use, and hot water use. This data will be used to formulate a model of the whole building envelope that can predict energy usage of future residential buildings and be used as the plant in a home automation/energy management control system.

The first steps in this project and reported in this paper include defining the sensor system configuration in the experimental houses (*i.e.*, the S&T solar village homes) to support the development of the energy model and the control algorithms. Figure 2 is a representational block diagram of the overall research approach.

Figure 2. Research approach block diagram.



2. Results and Discussion

Step 1 of this research approach involves identifying performance metrics on which to compare each of the S&T solar houses. In the following sections, the important performance metrics are identified and selected and the resulting sensor configuration is outlined.

2.1. Performance Metrics

The National Renewable Energy Lab (NREL) has published practices with the intent of standardizing the measurement and performance analysis of buildings. This is through the Performance Metrics Research Project [3] for the Department of Energy (DOE). These procedures will be used as the standard in this project.

The "Procedure for Measuring and Reporting Commercial Building Energy Performance" [4] published by NREL is used as a basis for the energy monitoring and reporting of this project. The paper identifies performance metrics for commercial buildings with the intent of standardizing sensor and information systems. Considering the building energy performance project was designed for commercial buildings, some metrics and data collection strategies will be adjusted to better fit a residential application.

The data collected for the NREL building energy performance has the possibility to be used in the following scenarios:

- Compare performance with the design intent of the building
- Compare performance with other buildings
- Evaluate building performance rating systems
- Perform economic analysis of energy-efficient strategies in buildings
- Establish long-term performance records that enable maintenance staff to monitor trends in energy performance.

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 adjusted metrics that are adopted with some adjustment for this project include the following:

2.1.1. 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.

2.1.2. 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.

2.1.3. 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.

$$\text{TEP} = \dot{V} \cdot \rho \cdot c_p (T_{output} - T_{input}) dt \quad (1)$$

2.1.4. 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.

2.1.5. 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 are 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.

$$\text{FEP} = \text{PVEP} + \text{TEP} - \text{EGSL} \quad (2)$$

2.1.6. 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.

2.1.7. 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.

2.1.8. 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.

2.1.9. 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.

2.1.10. 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.

2.1.11. 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.

2.1.12. 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.

$$DHWLoad = \int \dot{V} \cdot \rho \cdot c_p \, (T_{HW} - T_{CW}) dt \tag{3}$$

2.1.13. 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.

2.1.14. 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.

$$DHWSE = DHWL/DHWEU \quad (4)$$

2.1.15. 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.

2.1.16. Building Lighting Energy Use (BLEU)

This sums all energy used for lighting purposes including permanently installed indoor lights, lights that are plugged in, and exterior lighting. For this metric, lighting circuits must be measured individually or measured in such a way that other loads can be determined and subtracted. Lights that are plugged into outlets will be a difficult for this metric, but will be estimated by predetermination of floor lights and load analysis of the outlet circuits.

2.1.17. 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.

2.1.18. Building Energy Use (BEU)

This metric is the sum of all energy consumed by the house. This includes heating, ventilation, air conditioning, indoor lighting, façade lighting, domestic hot water, plug loads, 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.

2.1.19. 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.

$$BEUI = BEU/FA \quad (5)$$

2.1.20. 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.

2.1.21. 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.

2.1.22. 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.

2.1.23. 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.

2.1.24. 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.

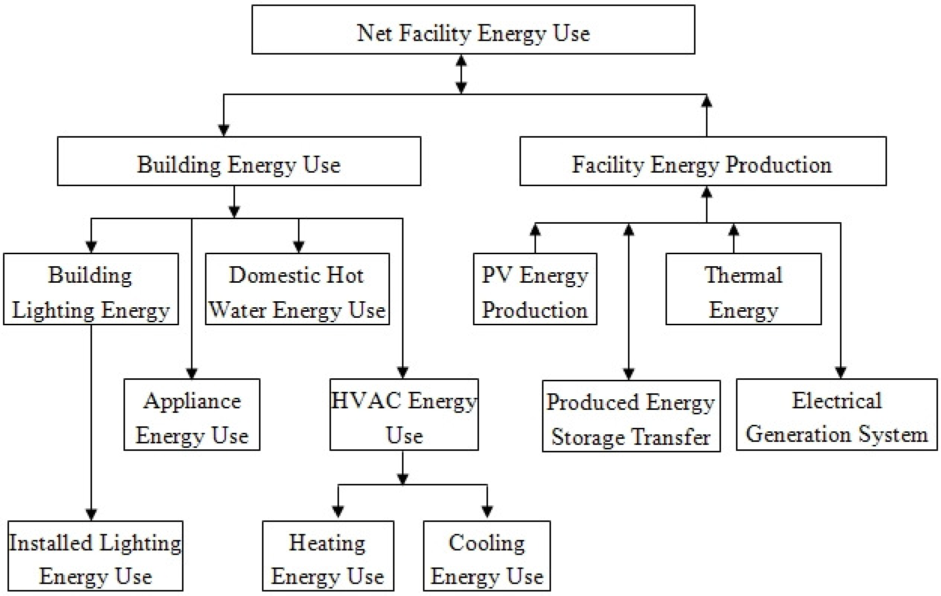
$$BPECI = BPEC/FA \quad (6)$$

2.1.25. 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 3 shows the relationship between all energy use metrics that were identified above. As shown, 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" [4].

Figure 3. Related energy performance metrics.

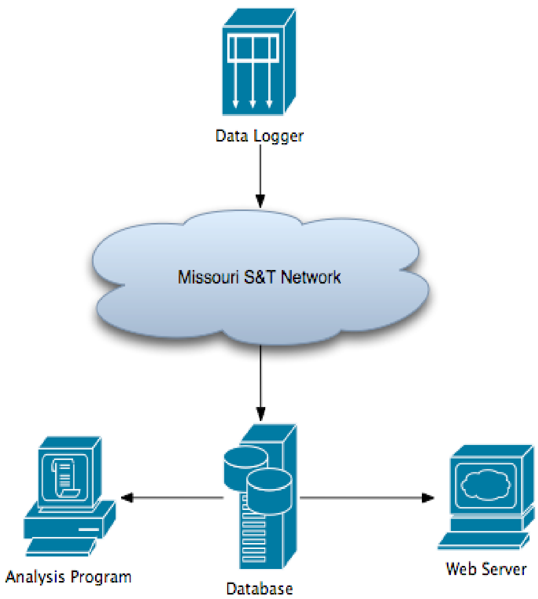


3. Experimental Section

3.1. Sensor Network

In modeling the entire building envelope and to measure the previously mentioned list of metrics a sensor and data logger network is installed in all three 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 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 4 below.

Figure 4. Sensor system architecture.



3.2. Identified Sensors

Table 1 lists all data that is being collected for each house and relates it to the use and purpose for that information. The "type" column is the kind of measurement and the "description" column explains the location of the measurement in relation to the house systems. The frequency of the measurement depends on the rate at which the data will be measured. Spot checks are one-time measurements that will be used to determine metrics such as the HERS index, which is a home energy analysis rating from Energy Star that provides an easily understandable means to compare the relative energy efficiency of different homes. The 5-second data includes items that may be changing quickly such as water flow. Faucets and toilets, for instance, are often using water for seconds at a time. Electrical data is also effectively being collected many times a minute, but the data is averaged and only logged once a minute. The "purpose" column identifies the analysis in which the data will be used.

Table 1. Sensor description, purpose, and measurement frequency.

			Purpose			Frequency		Measurement Quantity		
Description	**Type**	**Units**	**Model Calibration**	**Weather File**	**Occupancy Behavior**	**1-minute data**	**5-second data**	**2002 House**	**2005 House**	**2007 House**
Outside air	Temperature	F		x		x		1	1	1
Outside air	Humidity	%RH		x		x		1	1	1
Solar radiation	Solar Radiation	W/m2		x		x		4	4	4
Wind speed	Speed	mpg		x		x		1	1	1
Wind direction	Direction	degrees		x		x		1	1	1
AC energy drawn by 240V branch circuits	AC Energy	Wh			x	x		4	4	4
AC energy drawn by 120V branch circuits	AC Energy	Wh			x	x		16	16	16
Refrigerator	Temperature	F			x	x		1	1	1
Freezer	Temperature	F			x	x		1	1	1
Clothes washer	Temperature	F			x	x		1	1	1
Clothes dryer	Temperature	F			x	x		1	1	1
Dishwasher	Temperature	F			x	x		1	1	1
Cold water mains	Volumetric Flow	gallons			x		x	1	1	1
Domestic hot water	Volumetric Flow	gallons			x		x	1	1	1
Cold water mains	Temperature	F	x		x		x	1	1	1
Domestic hot water	Temperature	F	x		x		x	2	2	3
Supply air	Temperature	F	x			x		1	1	1
Return air	Temperature	F	x			x		1	1	1
Bi-directional AC energy to/from grid	AC Energy	Wh	x			x		1	1	1

Table 1. *Cont.*

Bi-directional AC energy to/from inverters	AC Energy	Wh	x	x	2	2	2
Hydronic heating and cooling loops	Temperature	F	x	x		8	8
Hydronic heating and cooling loops	Volumetric Flow	gallons	x	x		1	1
Various spaces and surfaces	Illumination	fc	x	x	3	3	3
PV cell	Temperature	F	x	x	4	4	4
PV strings	DC Voltage	V	x	x	4	4	4
DC bus	DC Voltage	V	x	x	1	1	1
PV strings	DC Current	A	x	x	4	4	3
Charge controllers	DC Current	A	x	x	4	4	3
Batteries	DC Current	A	x	x	1	1	1
Inverters	DC Current	A	x	x	2	2	2
Collector loop	Volumetric Flow	gallons	x	x	1	1	1
Collector loop	Temperature	F	x	x	2	2	2
Hot water storage tank	Temperature	F	x	x	3	3	3
Conditioned zone air	Temperature	F	x	x	2	2	2
Conditioned zone air	Humidity	%RH	x	x	2	2	2
Unconditioned zone air	Temperature	F	x	x	1	1	1
Unconditioned zone air	Humidity	%RH	x	x	1	1	1

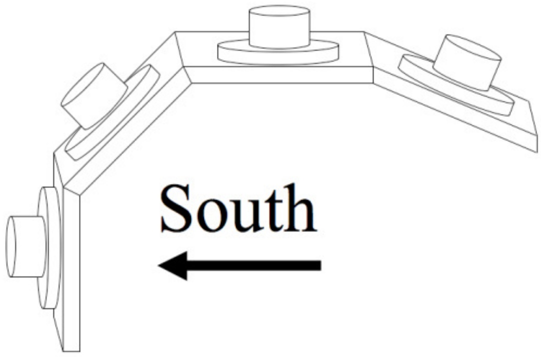
The "model calibration" column includes items that have little user influence, the occupancy behavior sensors will have data that will be heavily influenced by the user and the weather file is outside ambient conditions that will be used in determining performance. The "measurement quantity" column identifies the number of sensors that are in each house. The label of "all" in the measurement quantity identifies a spot check and that there are no permanent sensors to log data.

3.3. PV Performance

Following the "Procedure for Measuring and Reporting the Performance of Photovoltaic Systems in Buildings" [5] 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 3 houses with five 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 5 shows a diagram of the aforementioned pyranometer array.

Figure 5. Pyranometer array.



To follow the NREL procedures, electrical power sensors will be located between the inverters and breaker panel (1&2), grid and breaker panel (3&4), and all house loads (5). See Figure 6 for a schematic of the electrical sensor locations. Other 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.

Figure 6. Electrical sensor locations.

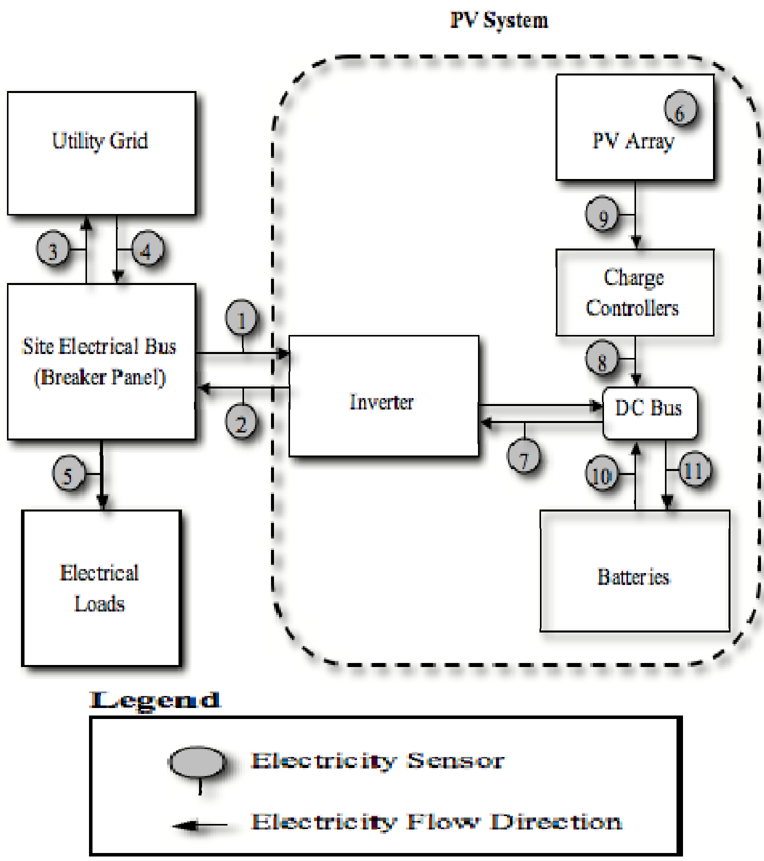


Table 2. Electrical sensor descriptions.

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

The metric of the data that is collected from each sensor is listed in Table 2. The NREL performance metrics are sensors 1 through 6 and the additional sensors that have been added for this project are 7 through 11. 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.

3.4. HVAC Performance

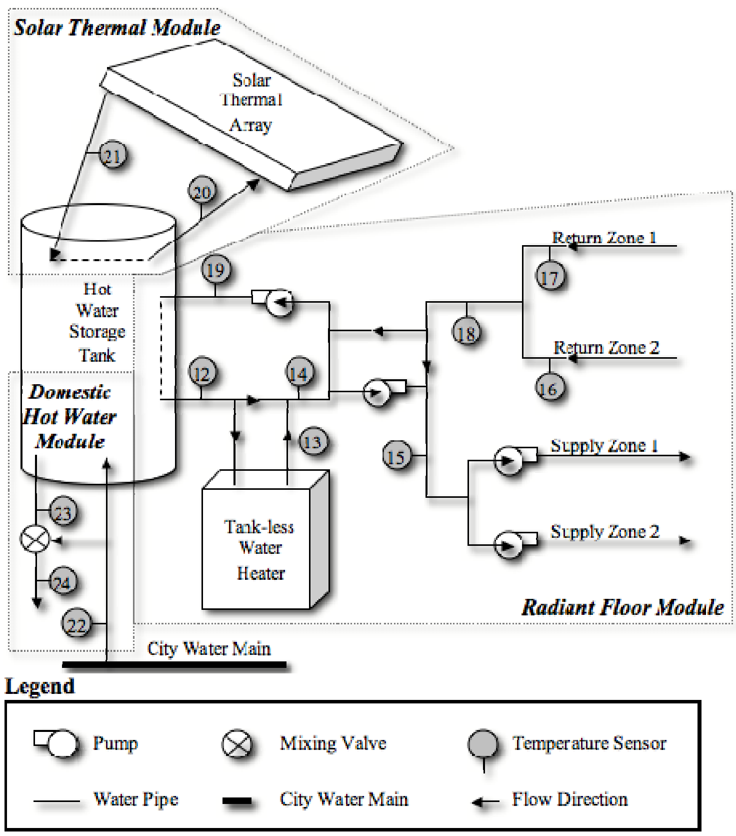
There are four different types of HVAC systems in the houses that will be involved with this project. The 2002 house incorporates a heat pump for heating and cooling plus an electric furnace for supplemental heating during times when the heat pump is inadequate at the ambient temperature. The 2005 and 2007 houses have a radiant floor for heating and an efficient heat pump or condenser unit air conditioner for cooling. A home automation system in the 2007 house opens 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 7 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. Table 3 lists the sensors and corresponding metrics.

Table 3. 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

Figure 7. Hot water systems temperature sensor locations.



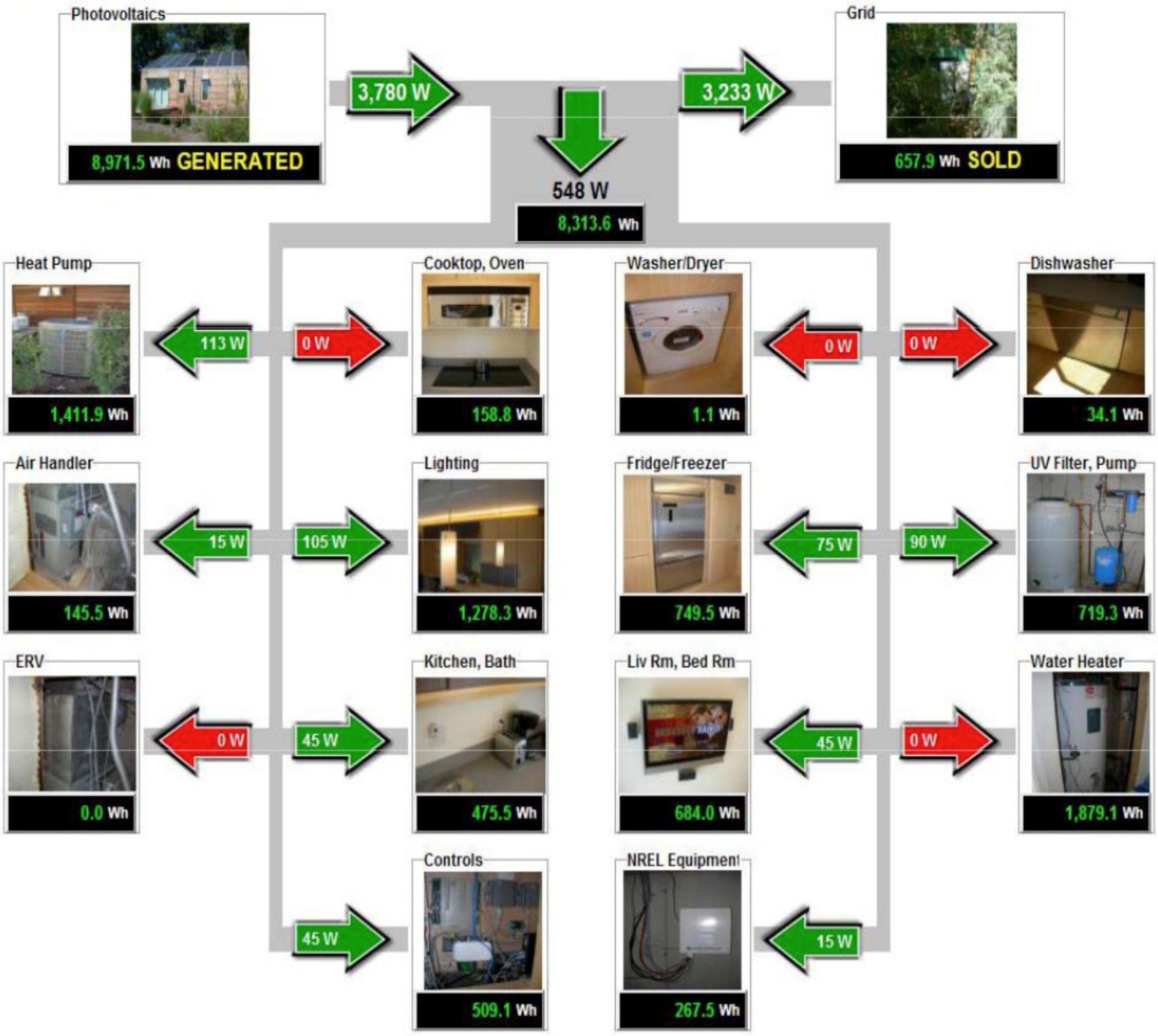
3.5. Feedback Interface

The data in the database is displayed in an intuitive web interface for the house tenants to view and understand. The electrical energy display, for example, is a basic line diagram of the house circuits. It displays the PV Energy Production, Net Facility Energy Use, and individual appliance usage with instantaneous power draw and daily totals. The display must be intuitive and easy to understand for the general user to gain the most advantage from the feedback interface. For this reason the display uses arrows and colors to identify the quantity and direction of power flow. Figure 8 is a snapshot of the web interface. 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 essentially operate a net zero energy home.

3.6. Resident Performance Survey

Along with the sensor data, each resident will be asked to track their energy consumption. They will record their usage of every electric consuming device by the duration in which they use it and the time of day that they use that particular electric item. Multiple days will be surveyed to average the electricity consumption habits. For instance, on a general day the resident uses the stovetop for 35 minutes and the microware for 5 minutes between 5:00 pm and 6:00 pm then turns on the television for 70 minutes starting between 6 pm and 7 pm. This data will be used to compare the measured energy data using the sensors with the perception and general habits of energy consumption from the resident. The sensor data and the resident survey will be used as inputs to the energy software to model the houses in step 3 of the research approach.

Figure 8. Web interface [6].



4. Conclusions

This paper describes the current effort at Missouri S&T to sensor and the whole building envelope of multiple solar-powered residential houses for the purpose of comparing performances and improving efficiency. The two approaches to energy efficiency research that are being pursued include building design modeling and energy feedback. The houses have been outfitted with a sensor network to record electrical building energy data work is in progress to complete thermal and ambient conditions data. The collected data is being stored in a database for building research purposes and displayed to tenants for energy use knowledge.

Future work based upon this initial village sensor project includes:

1. Developing a building energy use model based upon the homes.
2. Validate energy modeling programs with data collected at solar village and identifying possible improvements.
3. Identifying a marketable residential sensor network.
4. Developing performance control algorithms.

Other possible future work could be to build a home automation system based on energy use analysis to assist the homeowner in being energy efficient. This system could control appliances to run them during optimal times. This would be especially advantageous on homes with solar energy collection systems such as photovoltaic and solar thermal systems. Optimal times to run appliances in homes with these systems would be during solar noon when the maximum electricity and thermal energy are being produced.

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