Final Progress Report

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Project Objective: The objective of this project is to promote awareness and knowledge of active solar energy technologies by installing and monitoring the following demonstration systems in Kentucky: 1) Pool heating system, Churchill Park School, 2) Water heating and daylighting systems, Middletown and Aiken Road Elementary Schools, 3) Photovoltaic street light comparison, Louisville Metro, 4) up to 25 domestic water heating systems across Kentucky. These tasks will be supported by outreach activities, including a solar energy installer training workshop and a Kentucky Solar Energy Conference.

Background: The goal of expanding the use of active solar energy in Louisville is rooted in the Partnership for a Green City, a collaboration of the Louisville Metro government, University of Louisville and the Jefferson County Public Schools. Its goals are to improve the environment and public health, develop holistic environmental education programs, and to create a sustainable community, saving taxpayer dollars and conserving energy in the process.

Due to low energy costs and a lack of retailers, installers and awareness of the potential for solar systems, there are only a limited number of active solar systems installed in Kentucky. Yet with relatively mild winters and approximately 2/3 the solar radiation of the desert southwest, many solar technologies are viable and appropriate here. Energy costs are rising, and some commercial infrastructure has begun to appear, in part due to the efforts of the Kentucky Solar Partnership. With growing concern about pollution and climate change, this project seeks to stimulate the development of solar energy businesses and solar energy utilization within Kentucky.

Status: Throughout the grant period, one PhD and two MS students graduated on grant projects. In addition, one postdoctoral student, two PhD students and 34 Master of Engineering graduate students worked on projects related to the grant.

Task 1. Frankfort (KY) YMCA Pool Heater –The focus of this task was the refurbishment of the solar pool and domestic hot water heating system at the Frankfort (KY) YMCA. The 56 AET-40 collectors (2240 sq. ft.) were installed on the building (see pictures below). The contractor was able to use the existing racks. Aluminum mounts were attached directly to the racks at a 15% angle to allow for drain back. An old storage tank located in a closet directly below the array on the second floor of the YMCA was cut up and removed. Installation of the system was completed in February, 2010.

Task 2. School Solar Water Heaters – From summer 2006 to summer 2008, three solar water heating systems were installed on Jefferson County schools - Churchill Park, Farmer Elementary and Ramsey Elementary. The Farmer Elementary building is identical to the Aiken Road school built at the same time, but without solar. These two buildings allowed comparison of utility bills to determine the benefit of the solar system. In addition to its solar water heating system, the Ramsey school included light shelves and light tubes for daylighting, and a wind turbine. As a result of these initial projects, the school district instituted a policy to use solar water heating on all new Jefferson County schools.

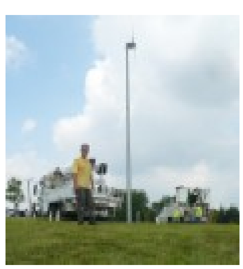
The Farmer system was installed in June 2007, and is a drainback, indirect, active system. The system consists of eight collectors, manufactured by Solar Energy Inc (model # S6-32) with a total absorption area of 21.672 square meters (233.2 square feet). The eight collectors are on a sloped rack facing south. The absorber is a roll-formed copper plate and collector glazing is one

sheet of low iron tempered glass. The SRCC has rated the thermal performance of the collector, at a ΔT of 36°F with clear sky radiation, at 27,100 Btu's per day (or a total for the rack equal to 216,800 Btu's). The collectors have been certified by the Florida Solar Energy Center (FSEC). A 30% mixture of glycol and water are circulated through the collectors and drain back into a 272 liter (60 gallon) tank. Each collector has a fluid capacity of 3.7 liters, or 29.6 liters total. The system is active with an AC pump being used to circulate the glycol/water mixture up to the roof-top mounted collectors.

The heated fluid is pumped through a heat exchanger and heat is transferred into a 500-gallon storage tank. The tank is a jacketed insulated, glass lined, constructed by A.O. Smith to meet ASME requirements (125 psi). The temperature differential controller is manufactured by Steca (model TR 0603) and has the capability for 28 pre-programmed systems and numerous additional functions allow universal use of the controller. Temperature data is inputted from the collectors, the bottom of the storage tank, water within the tank, and the water exiting the storage tank. When a 10°F temperature difference between the tank bottom and collector is reached, an AC pump is activated to transfer the glycol/water mixture up to the collectors.

Solar tanks, Churchill Park School

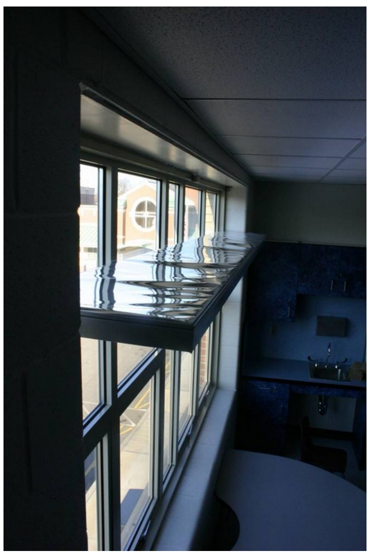
As a result of the new Jefferson County Public School policy, in July 2009 a solar hot water system was installed at Cane Run Elementary School. The system that was installed is a drain back design to provide hot water for the school. The school also installed geothermal heating and a 1.9 kW Skystream wind turbine. On windy days, the turbine helps supply power for the school by converting kinetic energy from the wind into electricity to be used by the school. Because the Skystream wind turbine does not interfere with television reception, is extremely quiet and cannot generally be heard over typical background noise, it is ideal for the school. The 45-ft tower was installed at the school by the Louisville Gas & Electric Company gratis. An installed monitoring system allows teachers across the district to explore a multitude of topics including weather, energy production, dollars saved and mechanics. The installation was completed on August 9, 2009.




The Ramsey Middle School in October 2009 was designated an EnergyStar school with a score of 95, the highest in the state. Their high score was due in part to the solar thermal system, daylighting and light shelves, and wind turbine installed at the school, funded partially through this grant. (Another Jefferson County school, Shelby Elementary, was the location of a light shelf study conducted through this grant (see below), was one of the first schools in the state designated as EnergyStar in 2006.)

Task 3. School Solar Daylighting Project –The local school district and the University examined a number of different light shelf designs, but found little comparative analyses of different designs. The University of Louisville Renewable Energy Applications Laboratory, in collaboration with the school district, conducted a feasibility analysis of 3 designs for light shelves to assess their performance. The 3 systems included:

1. 16” wide shelf—a prototype light shelf was built using box aluminum channels commonly used for screen porches, with a reflective mylar film (2 mm thick, 90% reflectance) instead of a screen.
2. 24” wide shelf—a similar prototype constructed of box aluminum frame and reflective mylar film.
3. LightLouver System—A unit of angled, reflective blades similar to a fixed venetian blind. The patented, passive optical design redirects daylight deep into a room while eliminating all direct sunlight penetration onto work surfaces. The angled blades reportedly reflect up to 76% of direct sunlight into a room, and on overcast days they are said to throw around 54% of the available light inside.


16” light shelf, Shelby Elementary

The first two systems were fabricated locally, while the third system was purchased directly from the manufacturer. All three systems were installed in August 2006 in the Shelby Elementary School in adjacent rooms. A fourth adjacent room was used as a control. Each room was divided into 36 point grids to measure the light gain from each of the three systems. Measurements were taken in the fall and early winter of 2006 to measure light levels on cloudy and sunny days, during the morning, midday, and afternoon. A Mannix DLM2000A 3 range digital light meter was used to measure light levels at the window, at the first row of seats and at each of the 36 points on the grid. Pictures were taken to provide visual data on light penetration into the rooms. The light levels were analyzed to determine which system provided the most light gain. The conclusion of this study was that the 16” light shelf provided the most light gain. The school district is now working with their contractors and architects to install similar light shelves into both schools.

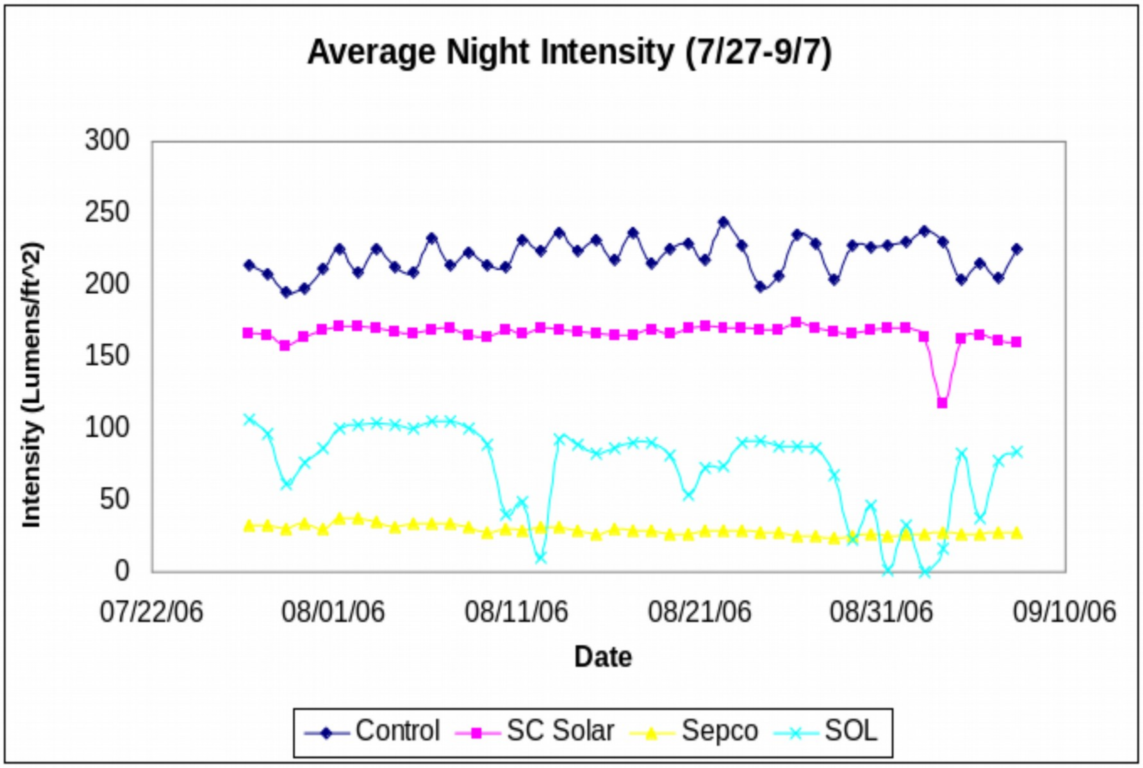
Average light distribution in rooms

The school district chose the 16” wide shelf for installation in the Billtown Road and Aiken Road Elementary Schools. Construction of both schools was completed July, 2007, including in all south facing rooms dimmable ballasts with light sensors to reduce the wattage being used when natural light is available.

Task 4. Photovoltaic Street Lights – Three photovoltaic street lights were purchased for evaluation for the Louisville Metro government. They were evaluated over a 6 month test period (July 2006-January 2007) to assess their performance. The three PV systems tested were:

1. South Carolina Solar - Uses HID bulb (100-125 lumens/watt),Sharp PV cell (170 watt), Battery (2, 180 amp hours)
2. SEPCO - Uses CFL bulb (60 lumens/watt), Shell Solar PV cell (225 watt), Battery (2, 200 amp hours)
3. SOL - Uses CFL bulb (60 lumens/watt). BP Solar PV cell (250 watt), Battery (2, 200 amp hours)

The Mayor requested that the lights be installed downtown for greater public visibility, so they were installed directly north of the city hall between 6th and 7th streets on June 13, 2006. Light sensors and data loggers using Hoboware software were purchased and installed under each light, and a fourth sensor and data logger were placed as a control under an existing AC powered streetlight. Light intensity (lumens/ft^2) and temperature were recorded every 5 minutes throughout the test period. Output was downloaded onto PCs every 6-8 weeks and transferred to Excel spread sheets for analysis.



The University of Louisville Renewable Energy Applications Laboratory conducted a feasibility study of the three alternative streetlights. The data was assessed for light intensity over 12 hour periods of time, and the duration that the streetlight was on each night. The averages in the first two months of the test period are shown below. During the summer months, the streetlights all stayed on from dusk to dawn. The data showed that one of the streetlights had a shortened duration when there were two or more days of cloudy weather. The manufacturer visited Louisville in October 2006 and after some discussion concluded that the system was not wired correctly during manufacture. The company sent a new controller that was installed in November 2006. After the testing, these streetlights were moved to remote parking lots of the Floyd's Fork Park where electricity is otherwise unavailable.

Overall during summer months, the streetlights performed as expected even when there were up to 4 days of cloudy weather. The light intensities for all of the PV powered streetlights were less than the control. Qualitatively, the compact fluorescent lights provided the least light. The quantitative light intensities from each light could not be assessed in this location, because of interference from other light sources. However, the collected data confirm that PV systems provide reasonably reliable light throughout the night during typical Louisville weather, at least into early fall.

Task 5. Solar Education – The University partnered with the State Fair Board to prepare educational exhibits and demonstrations on solar energy for the Kentucky State Fair August 17-27, 2006. This was the 15th year that the State Fair included an Educational Program. The Fair Board dedicated 20,000 square feet of indoor space, plus another 1,000 square feet of outdoor space to energy education. The audited paid attendance to the State Fair was 614,477 individuals. This includes 13,320 K-12 students who visited the educational exhibits on formal field trips. This set a new record for field trips to the State Fair educational program (previous record was 11,874).

In April and May, 2006, eighty seven teachers attended Professional Development (PD) sessions taught by Russell Barnett (UofL) and Stephanie Darst (State Fair). The sessions were designed to increase teachers awareness of energy issues, alternative energy sources including solar energy, learn about the opportunities for students to learn about solar and other energy issues, and to provide them with background materials on energy. These sessions helped increase interest in the energy exhibit. These teachers helped review lesson plan drafts and exhibits to make them more compatible with school curriculum and understandable to K-12 students. A copy of the curriculums developed are available at http://www.kystatefair.org/special_exhibits/educational_exhibit/teachers_students/educational_exhibit2.html

The Solar exhibits at the State Fair included:

* Solar Energy Garden
* Model Home with BIPVs
* Solar Hot Water System
* Heliodon
* Passive Solar Energy Panel

Solar Energy Garden. A solar energy garden was constructed outside to demonstrate the use of BIPV. Three 62 watt PV panels manufactured by Unisolar (PVL-62) were purchased to provide energy to run a DC-powered pump. The photovoltaic laminated (PVL) panels use UV-stabilized polymers, partly constructed of durable ETFE, a high light-transmissive polymer to provide flexible almost indestructible PV power. The panels have a “peel and stick” back and can be easily attached to commercial metal roofs. A small 8’X10” open-sided shed was built with a commercial-quality metal roof. The roof was donated by Howard Hardware Inc., Chaplin, Kentucky. A Grundfos 25 SQF-3 DC power pump was connected to the photovoltaic system and was used to pump water up to the top of stacked stones to create an artificial waterfall. The system demonstrated the use of BIVP to generate sufficient energy to pump large volumes of water. At the conclusion of the State Fair, the shed and pump were transported to the Jeffersontown Elementary School and permanently installed as a centerpiece to the school’s outdoor classroom.

Model Home with BIPVs. The concept of building integrated photovoltaics is one of the most promising renewable energy technologies, but has not seen many applications in the Commonwealth of Kentucky. A 4’X7’X4’ model home was constructed and painted by an University art student. The model was designed to break down easily for transportation in a van or pickup truck. The roof of the model home has asphalt shingles and two solar shingles manufactured by Unisolar and a 62 watt shingle manufactured by Sharp.

The model home is now part of a traveling exhibit and has been shown across the state including: 5 schools in Jefferson County, an Energy Expo in Lexington (Oct 6-7, 2006), and a science fair in Lexington (March 3, 2007).

Solar Hot Water System. A demonstration size (3'X1.5') solar hot water system was purchased and mounted in a display to show how solar hot water systems work. The system demonstrated was a Guardian, manufactured by LeverEdge. The system uses natural convection to circulate water from a 5-gallon bucket, through the solar panel, out and draining back to the bucket. A large thermometer was installed on top of the bucket to measure the amount of heat transferred to the water.

The hot water system is also part of the traveling exhibit to continue educating people on the use of solar energy to meet household needs.

Heliodon. Two Graduate Research Assistants designed and constructed a heliodon to match the solar altitude and azimuth angles for any day at a specific latitude. Heliodons are used primarily by architects and students of architecture. By placing a model building on the heliodon's flat surface and making adjustments to the light/surface angle, the investigator can see how light will penetrate through windows in the building at various dates and times of day. A heliodon can assist architects in designing buildings to maximize passive solar potentials. The students trained individuals who were at the fair full time on the mechanics and purpose of the heliodon.

The heliodon is part of the traveling exhibit and is available for use by architects and students (see Task 8 below). The heliodon was also on exhibit at the Energy Expo in Lexington (Oct 6-7, 2006).

Passive Solar Energy Panel. Two Graduate Research Assistants at the University designed, edited and constructed a series of panels on passive solar energy designs. The exhibit includes 4 framed panels (total of 8 panels front-and-back) designed for easy set up and transportation. The metal frames were welded by the students. The panels describe passive solar fundamentals, its benefits, design techniques, and the energy and cost savings from passive solar.

The panel is part of the traveling exhibit.

Task 6. Residential Solar Hot Water Heaters – The Kentucky Solar Partnership (KSP) was contracted to implement a pilot rebate program for solar water heaters. The rebate program was established in January 2006. Twenty five $500 rebates were made available for solar water heaters installed on residences in Kentucky. KSP established guidelines for the types of systems that could be installed through the program (e.g. pressurized glycol or drainback systems using SRCC rated collectors, etc.). Applications for all 25 rebates were received and approved by KSP.

KSP's staff inspected each installation through this program. Several systems failed the first inspection. In one case, thermometers installed in the collector loop to monitor collector performance were producing inconsistent temperature readings. A loose wire on the storage tank temperature sensor was connected and a new digital differential controller was installed, but at the time of this report the system is still not working properly. Follow-up inspections were scheduled to correct the problems. Another system had a collector with broken glass. The installer was called and replaced the collector within several days. The installer said the breakage was due to a manufacturing defect in that collector. The third system had a number of problems related to water pressure and temperature. At KSP's suggestion the homeowner had the water pressure coming into his property tested and it was found to be extremely high. This explained the problems. The installer returned and installed a pressure control valve on the water supply line to the house, which corrected the problem. He also addressed a number of other shortcomings with the system on that visit. On the fourth system, the homeowner was having water pressure problems in a third floor shower. At our suggestion the installer replaced a section of plumbing with larger diameter pipe and the problem was resolved.

The inspection process allowed KSP to provide valuable oversight and in-the-field training to a number of new solar installers. This has been one of the very valuable components of the project. KSP continued to receive inquiries about the availability of the rebates. They were found to be a valuable means of increasing market demand for solar water heaters and supporting contractors who were new to the business.

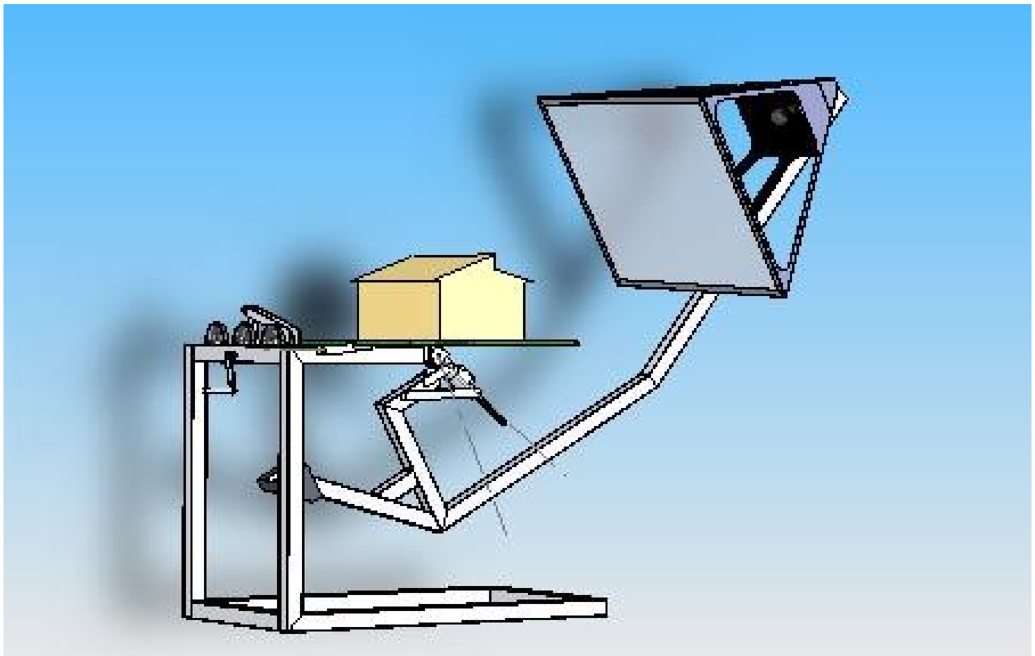
Task 7. Large PV Array –A 50.4 kW photovoltaic array was installed on the new Predictive Medicine laboratory located on the UofL Shelby Campus. At the time, the array is the largest in the Commonwealth. The 37,000-square-foot research lab became operational by early 2009. Scientists at the $34.6 million lab work to develop vaccines and other countermeasures for bioterrorism and emerging infectious diseases. The lab is one of 13 new Level 3 biosafety labs being built throughout the country with funding from the National Institutes of Health's National Institute of Allergy and Infectious Diseases. It is one that is built to meet LEED standards. The 50.4 kW photovoltaic system is estimated to generate approximate 64,000 kWh annually. The system generated an average of 143 kwh daily from March 21 to April 20, 2008. Through the summer the system generates close to 6,000 kWh monthly, but this represents only a fraction of the total electrical energy demands of the building. The modules selected are manufactured by General Electric (GEPVp-200) with a peak power of 200 watts at 26.3 volts and allow a maximum system voltage of 1,000 volts. The PVUSA rating for this module is 178.5 watts, or 11.4 watts per square foot, with an efficiency rating of 13.7%. The temperature coefficient is -0.5%/Co. They were installed in two arrays (north and south) with a total of 252 modules. Each 200 watt PV module has 54 poly-crystalline cells connected in series and has a manufacturer's guarantee for power output for 25 years, and workmanship for 5 years. This module meets both UL-1703 andIEC-61215 Version 1.0 standards.

The modules use SolarDock flat-roof mounting hardware made of aluminum with stainless steel fasteners. This mounting system makes no roof penetration, yet meets ACSE 7-98 criteria for 90 mph winds. The mounting system and solar modules adds

5-6 lbs per square foot to the roof. The rows of the array are tied together using aluminum "T" angles which run perpendicular to the rows every 10'-0" on center. This additional reinforcement allows the SolarDocks to resist the wind loads. The modules are held in place at a 25-degree slope that increases energy output over a flat installation. On the bottom is one-inch rigid foam insulation that protects the roof. The mounting system can be easily moved for any routine roof maintenance.

The North array consists of six parallel subarrays, each with 14 modules wired in series to increase voltage, (84 modules total). The south array contains 12 similar parallel subarrays (168 modules total). Both arrays are connected through a combiner into a Satcon 50kW Powergate Plus inverter. The utility-grade PowerGate incorporates a high-efficiency transformer and both AC and DC switchgear to disconnect the inverter at night, minimizing energy losses. A highly efficient wake-up routine maximizes the net energy harvest of the system. The system is not grid-tied since the energy demands in the building exceed the generating capacity of the PV system.

Task 8. Heliodon – Students in Mechanical Engineering at the UofL designed and built a portable heliodon in 2006. The heliodon uses a Fresnel lens to collimate light from a 1kW bulb to simulate the rays from the sun, and has hand cranks connected to graduated scales for adjustment of latitude and time of year. The light source is rotated manually to simulate sunrise to sunset, and a sundial is provided to indicate hour of the day. Improvements were subsequently incorporated by two additional student teams in 2007 and 2008. The heliodon was first featured in an energy exhibit at the 2006 Kentucky State Fair, and has since traveled across the state for a number of renewable energy functions. The heliodon has been used regularly in two mechanical engineering courses at the UofL, and is often displayed for prospective students, administrators and legislators. The declination scale on the heliodon was refined this quarter, and the unit was used for demonstrations in ME 667 Solar Energy Applications, and for several tours for administrators and high school students.



Task 9. Tracking PV/Thermal System - A two-axis tracker was installed on the roof of Sackett Hall, the home of the Mechanical Engineering Department. Two thermal panels were sized to supply nearly 100% of the buildings summer water heating needs and the majority of winter needs. Ten PV modules supply enough electricity into the grid to approximately power the buildings computer laboratory. A primary function of the system is for instructional laboratory experiments, for which instrumentation was installed, including a pyranometer, inclinometer, digital compass, flow meter, several thermocouples and a weather station. A flat screen monitor was also installed at the entrance to Sackett Hall for display of system data. This display, which has been viewed by hundreds of students per day, has raised awareness of solar energy systems and increased interest in the renewable energy curriculum.

Task 10. Kentucky Solar Partnership activities –

PV installers workshops - Three workshops were conducted in spring 2006 and spring and fall 2008. The workshops provided hands-on system design and installation instruction for homeowners and commercial installers, as well as information for utility regulators. These popular workshops each had approximately 30 participants, and contributed to the development of two certified PV installation businesses in the state.

Solar Trailer mobile exhibit – Exhibited at state and local events, including the Madison County Energy Fair, Paducah Green Living Expo. Over 500 people attended the Fair and viewed the exhibit. Also made a 2 hour presentation on solar PV and solar thermal to over 50 participants at this event.

Public presentations on solar energy – Presentations across the state, including at the Franklin County Cooperative Extension Office, Kentucky Housing Corporation, Midwest Energy Star Conference, Louisville Energy Forum and the Grant County Public Library.

Assessments of solar water heater installations - Performed follow-up assessments on numerous solar water heater installations, some of which received rebates from our program in 2006 and some which received a loan from KSP's loan program. Performed preliminary analysis of performance data for solar water heaters at two Frankfort fire stations. Supported Berea College with installation of solar water heaters on four apartments with system monitoring equipment on each unit. Two units use flat plate collectors and two use Apricus evacuated tube collectors. Data will be collected and analyzed for one year to compare performance on different collectors and to compare real-world performance to RETScreen software estimates.

Solar energy workshops - Two workshops were held in Frankfort in April 2009. Workshops were presented by Bill Guiney, Renewable Energy Program Manager for Johnson Controls, Inc.

Solar water heaters on low-income housing - Established agreements with three low-income housing partners to work together to install solar water heaters on homes in their communities, using grant support from UofL. Partners include Habitat for Humanity of Madison and Clark Counties, People's Self Help Housing of Vanceburg, and the Kentucky Highlands Corporation of London, KY. This project began with a training seminar in April 2009 in Frankfort, Kentucky. Two construction managers from PSHH attended a two day workshop on the design and installation of solar water heating systems. The workshop was presented by Bill Guiney of Johnson Controls, Inc. In July 2009, solar water heating (SWH) systems were installed on two homes in Tollesboro, Kentucky. The project was coordinated by the Kentucky Solar Partnership. People's Self Help Housing (PSHH) was the local partner.

The two homes on which these SWH units were installed were built by PSHH in a subdivision PSHH is developing in Tollesboro, in Lewis County. PSHH builds homes for low-income families in northeastern Kentucky. The two homes involved in this project were designed to be highly energy efficient, as part of a project by PSHH to explore green building practices for their home designs. PSHH continued to build additional additional homes as part of this green building process.

This project met our objectives of training local professionals in the techniques for installing SWH systems, providing demonstration SWH for low-income housing providers and their communities, providing SWH for low-income families, and demonstrating that SWH systems can be installed at substantially reduced costs by non-profit housing providers using their own trained construction personnel, as compared with hiring professional solar installers to install the systems.

Other related activities included planning for the installation of additional SWH and training of other persons on projects with partners in Berea and Whitley County, Kentucky. The project in Berea will involve one drainback SWH to be installed on a new energy efficient home in December 2009, in partnership with Habitat for Humanity of Madison and Clark Counties. The project in Whitley County is being developed with the Kentucky Highlands Investment Corporation. KHIC is partnering with Oak Ridge National Labs to design and build three "zero energy homes" for low income families. The Kentucky Solar Partnership provided support for the installation of SWH on each of these three homes in the Spring of 2010.

Task 11. Passive Solar Heat Pipe System - *Simulations* - A set of programmed thermal networks were used to simulate the performance of several conventional passive solar heating systems, including direct gain, concrete wall indirect gain and water wall indirect gain, and that of a novel heat pipe augmented passive solar system (Fig. 1). Heat pipes provide one-way heat transfer into the building during sunny days,

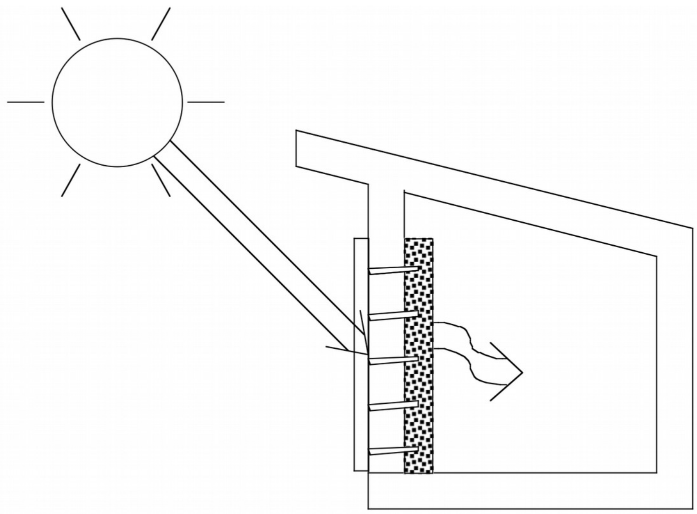


Figure 1. Schematic of the solar heat pipe system. Heat pipes provide one-way heat transfer from the absorber on the outside of the insulated wall to the storage medium inside the building.

with little heat loss out of the building during nighttime and cloudy days. In the evaporator end of the heat pipe, which is attached a an absorber plate, a heat transfer fluid is boiled and the resulting vapor travels up to the condenser end (Fig. 2). There the fluid condenses, transferring its energy to the interior of the building.

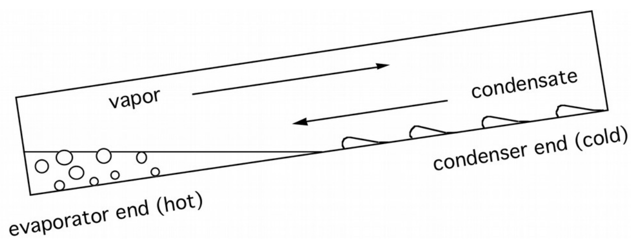


Figure 2. Schematic of a heat pipe.

Simulations were performed for Louisville, KY, Albuquerque, NM, Rock Springs, WY and Madison, WI to represent a range of winter temperatures and available insolation. Results showed that the direct gain system performed well in cool and sunny Albuquerque, but produced a net loss in cold and cloudy Madison (Fig. 3). The indirect gain systems performed better than direct gain in all locations but Albuquerque. The water wall system provided greater gains than the concrete wall in all climates. The heat pipe system performed significantly better than all other systems in all climates. The heat pipe system was especially advantageous in cold and cloudy Madison. In Louisville, the solar fractions were 22.4%, 30.8%, 38.8% and 50.7% for direct gain, concrete wall indirect gain, water wall indirect gain and heat pipe systems, respectively.

These performance values were better than those in Rock Springs, which is sunnier but colder, and considerably better than Madison, which is colder but only slightly cloudier. Though Louisville receives less solar radiation during the winter than Albuquerque and Rock Springs, it remains a favorable climate for solar heating because of its mild winter temperatures.

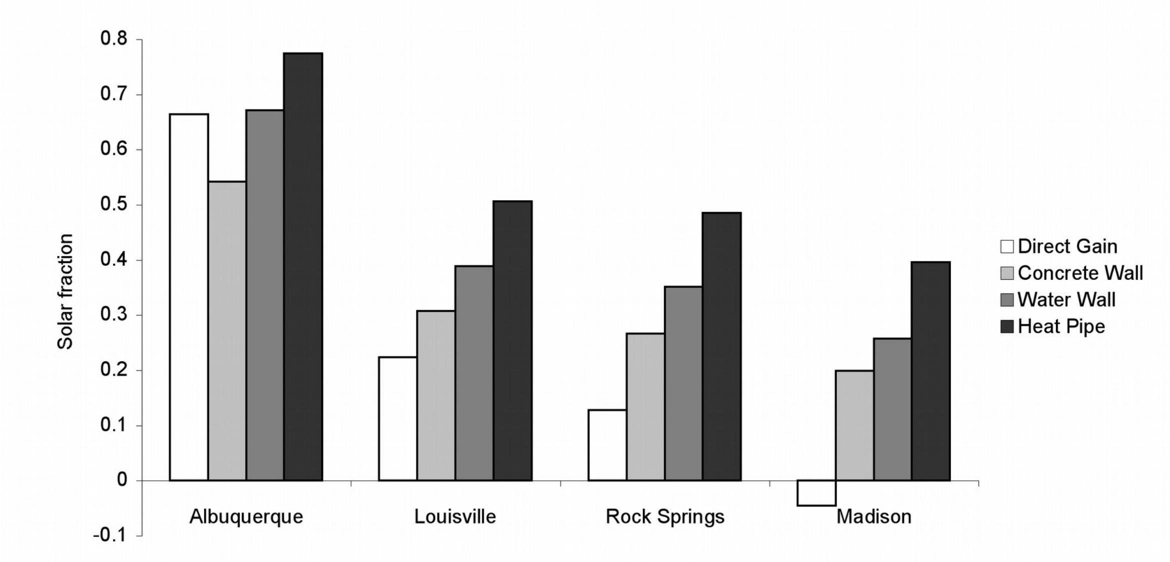


Figure 3. Comparison of the thermal performance of several passive solar heating systems.

Full-scale experiments – A full-scale prototype was constructed and installed in Burhans Hall on the Shelby campus. The system used low-iron glass, black chrome plated aluminum absorber, and five copper heat pipes and water tanks. The system was instrumented with a pyranometer and 31 thermocouples, eight each on the absorber, heat pipe and water tank of the central heat pipe unit, five in the remaining four water tanks, one for ambient temperature and one in the room. Data were first collected during spring 2009. Data was also collected during summer 2009 for two different conditions – shading from beam radiation by an overhang, and full shading by an opaque cover. Component temperatures were measured to quantify the amount of undesirable heat being added to the room during the cooling season. Data collection continued through 2010 until the unit was removed in late October. Via analysis of the thermal network connecting the thermal mass and the room, system peak efficiencies were calculated for every day investigated during the heating season. The maximum daily peak efficiency calculated was 83.7%, and the average daily peak efficiency calculated was 61.4%.

Modifications to improve performance were evaluated by computer simulations, including better thermal connection between the absorber and the evaporator section of the heat pipe, more insulation between the absorber and the storage tanks, an adiabatic section of lower conductivity (such as a hose rather than a copper pipe), and eliminating one storage tank to heat the room directly. The latter change was intended to provide quicker heating of the room in the morning. The combination of modifications was predicted to improve performance by about 16%.

Because the Shelby campus site was no longer available for testing, and no other suitable sites could be identified, a small test facility was constructed for further testing (Fig. 4). The 12' x 24' building was built with structural insulated panels (SIP's) for ease of construction, and is divided into two rooms with an insulated interior wall. The building allows side-by-side testing of two systems. Figure 4 also shows pyranometers, two on the south wall and two on the clerestory section, for quantifying insolation on these surfaces. Minor repairs were made to the original prototype and a new one with the simulated modifications to improve performance was constructed, and both were installed in the test facility.

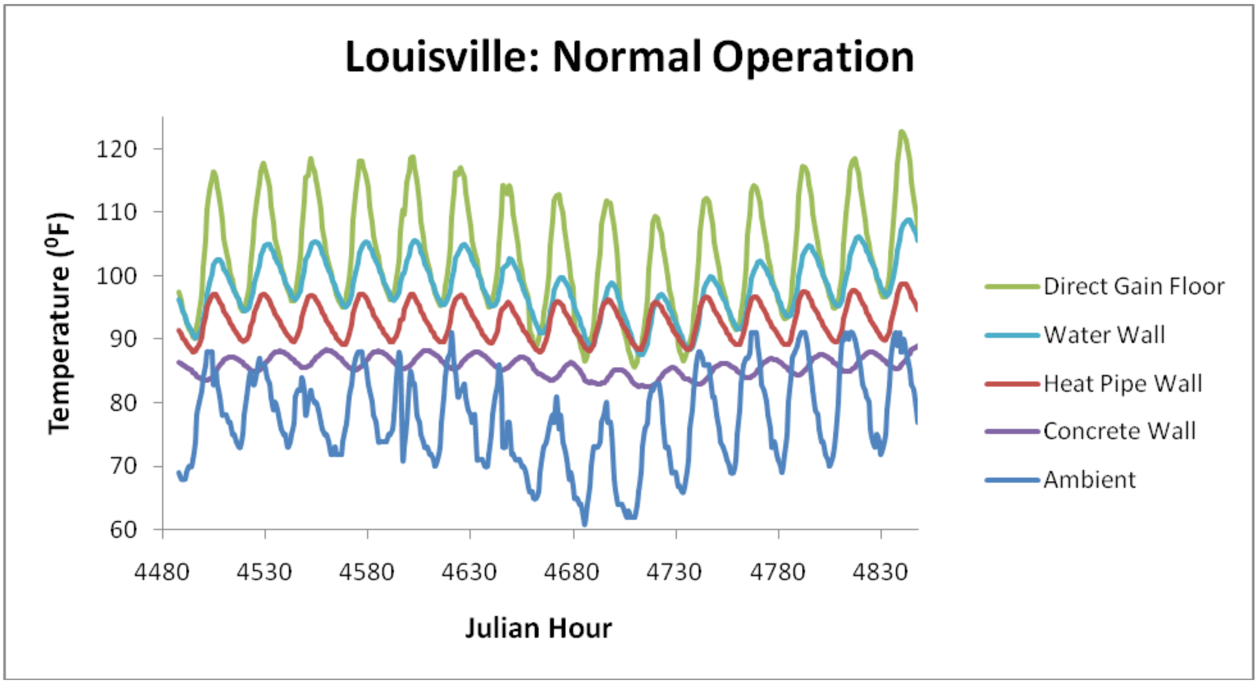
Initial cooling season data was collected during the summer, and heating season data was collected during the fall. A journal article in *Solar Energy* on the performance of the original prototype and simulations of the same system [Robinson, et al. 2013]. A conference paper was presented on the passive solar test facility. A second paper desccribes the heating season performance of the second prototype [Robinson & Sharp 2014].

Mechanisms for reducing unwanted gains were added for both systems during the fall, including an adjustable overhang and an opaque cover. The new prototype also includes a valve in the heat pipe to turn it off. These features will be tested during the cooling season of 2013.

Figure 4. Passive solar test facility with heat pipe systems installed.

Heating season simulations – The thermal network simulation program, previously used to study passive solar heating performance during the heating season only, was modified to study summertime overheating in passive solar systems, including direct gain, indirect gain water wall and concrete wall, and the solar heat pipe system. Both wintertime heating and summer overheating were calculated, so that the overall benefit of passive solar heating could be quantified.

The differences in unwanted gains during the cooling season among several passive heating systems were simulated and are demonstrated in the figure below, which shows wall or floor temperatures for each system located in Louisville, during the typically 'hottest' days of July 7 to July 21.



Passive heating normal operation temperatures in Louisville for 7/7 – 7/21.

During this period, the direct gain and water wall systems are hotter than the heat pipe system and, therefore, cause greater unwanted gains. Higher temperatures are present in the direct gain system due to the collection of solar radiation directly into the living space. The water wall temperatures are greater than the heat pipe in part because it doesn't employ a selective surface, allowing more thermal energy transfer to the thermal mass during nighttime. The concrete wall represents the lowest inside wall temperature due to moderating effect of conduction through the wall.

The effectiveness of shading strategies to reduce overheating were evaluated. Modifications to the simulations for using the new TMY3 data are complete. Climates for four different locations were simulated are shown in Fig. 5. Albuquerque and Louisville have similar cooling loads that are larger than those in Madison and Rock Springs, with Rock Springs having the lowest cooling loads and the shortest cooling season. Cooling seasons were designated as May – September in Albuquerque and Louisville, May – August in Madison and June – September in Rock Springs. Direct gain, concrete and water indirect gain, and heat pipe passive solar systems were analyzed. Shading strategies included shading from beam radiation only, and full shading by an opaque cover. In addition for the heat pipe system, a valve to turn off the heat pipe was evaluated. Unwanted cooling season gains were defined as when the systems heated the room to above a comfort temperature of 72 °F and ambient temperature was above a base temperature of 66 °F.

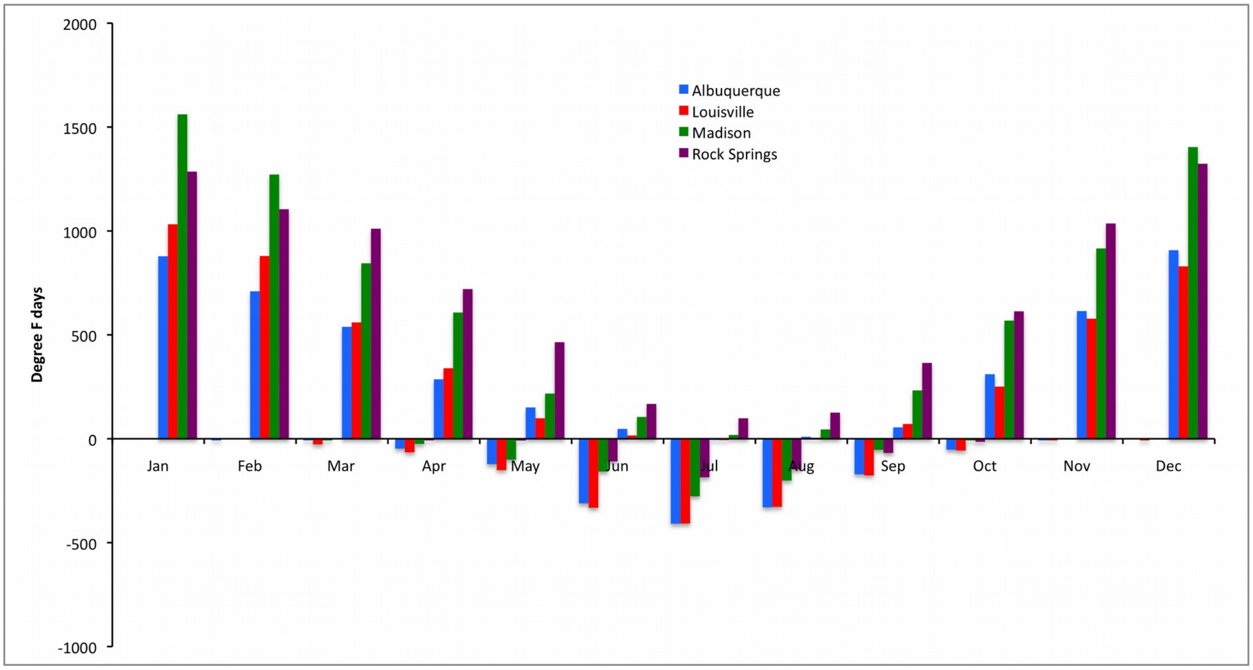


Figure 5. Heating and cooling degree ^{o}F days in four different climates. Cooling degree days are shown as negative. 66 ^{o}F base temperature.

These unwanted gains normalized by the nonsolar cooling loads during the designated cooling season are shown in Fig. 6. It is apparent that all passive solar systems increased cooling loads substantially when no shading strategies were used. The heat pipe and direct gain systems added more heat to the room than the indirect gain systems, which have thermal mass between the solar glazing and the room to moderate delivery of heat to the room. (The heat pipe system also has thermal mass in a similar position, but it was so much more efficient in collecting energy that the mass was warmed considerably more than that of the indirect gain systems.) The ratios of unwanted gains to nonsolar cooling loads were larger in Madison and Rock Springs, in large part because the nonsolar cooling loads were smaller in these climates. Shading the systems from beam radiation only, such as with an overhang, reduced gains significantly, but an opaque cover reduced gains to near zero in most cases. Closing a valve to turn the heat pipe system off left a small amount of unwanted gains by conduction through the insulated wall from the hot absorber, which was still being heated by the sun during the day. Even in combination with shading from beam radiation, the valve was less effective than the opaque cover.

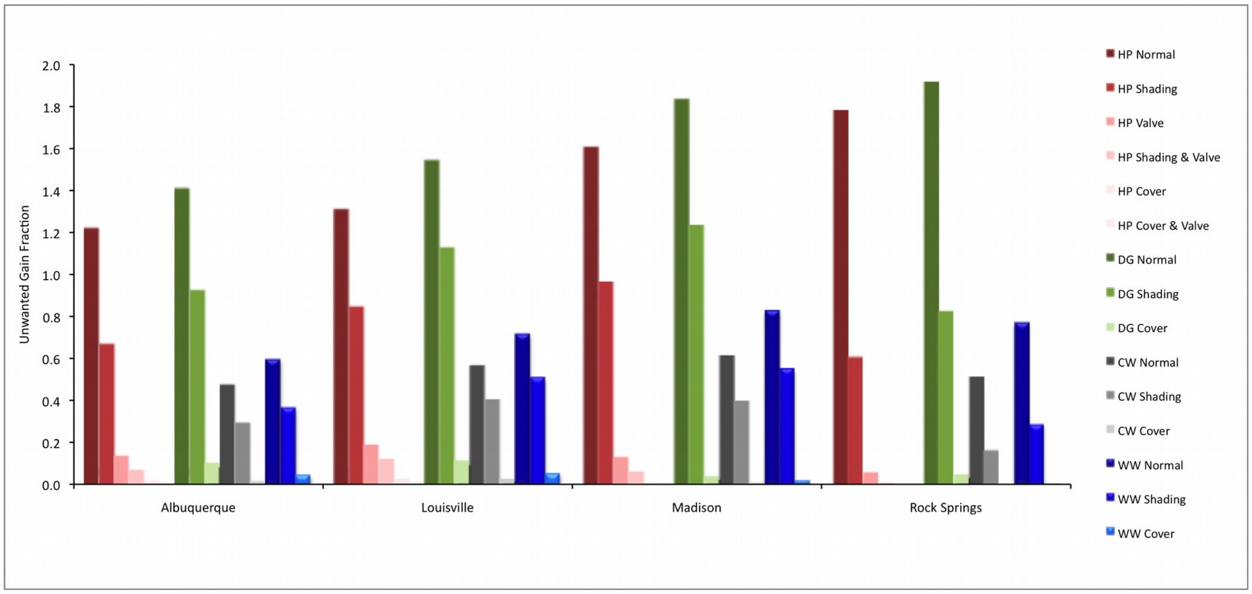


Figure 6. Unwanted gains in four different climates. HP – heat pipe, DG – direct gain, CW – concrete indirect gain, WW – water wall indirect gain.

Unwanted solar gains depend on the specified comfort temperature. In addition, the gains may be reduced by using a wide comfort temperature range in conjunction with thermal mass within the room, neither of which are currently incorporated into the simulations. These issues may be investigated in the future.

Four mechanisms were investigated in more detail for reducing unwanted gains to the solar heat pipe system during the cooling season: 1) shading that eliminates beam radiation, 2) a cover that eliminates both beam and diffuse radiation, 3) a valve that stops flow inside the heat pipe, and 4) switching the elevations of the evaporator and condenser sections so that the heat pipe transfers energy in the opposite direction (from inside to outside). Bench-scale experiments were performed to find the penalty for leveling the evaporator and condenser sections, which would simplify the switching mechanism to rotating the heat pipe in only one plane. This penalty (about 6%) was included in the simulations. For each mechanism, three control strategies were tested: 1) indoor temperature-based control, 2) ambient temperature-based control, and 3) seasonal installation/activation of the mechanism. These mechanisms and strategies were simulated in four different climates. For all climates and mechanisms, it was found that ambient temperature-based control produced the greatest reductions in unwanted gains. The cover, valve and switching provided the greatest reductions among the mechanisms, however because of the penalty for leveling the evaporator and condenser sections, heating performance for switching was less. The switching mechanism provided little cooling, due to the selective properties of both the glass cover and the absorber. The valve is perhaps the most convenient mechanism, since it is smaller and easier to deploy than the cover. A conference paper was presented on these simulations and a journal article has appeared [Robinson & Sharp 2015].

Work continues on simulations to predict the performance of an integrated passive solar heating/night sky radiant cooling/daylighting system that would incorporate electrochromic surfaces to switch among these modes. This system was conceived as an evolution of the heat pipe system with summertime cooling capabilities. The cooling performance of the heat pipe system during the summer was poor, because the optical properties of the system were optimized for heating, yet changing materials to improve cooling performance would compromise heating performance. The new integrated system would have switchable optical properties so that both heating and cooling performance are good. Significant materials development is needed to realize this system. These simulations are intended to document the performance potential of the new system.

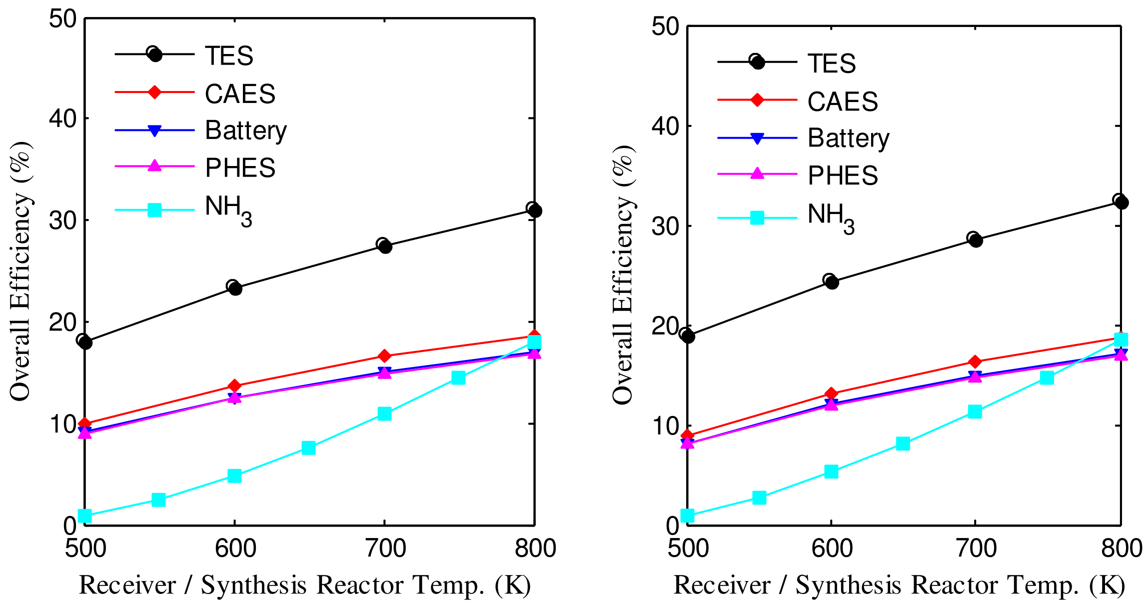
While the current simulations have been conducted using Matlab, other simulation environments may provide greater benefit to building designers. Two approaches were initiated. First, a simplified monthly performance prediction for the solar heat pipe system based on the Solar Load Ratio method was investigated. This method could, for instance, be implemented on a website with a few fillable windows for quick performance estimates and comparison with conventional passive solar systems. SLR parameters for the solar heat pipe system will be reported at the ASME Power and Energy Conference [Poteat & Sharp 2015]. Second, a module was programmed for heat pipe systems for incorporation into EnergyPlus, which provides greater flexibility and detail.

Ambient Sources - While solar energy provides a relatively universally applicable source for passive space heating across a variety of climates, other ambient energy sources may be more appropriate for passive space cooling. These ambient resources include ambient air at dry-bulb temperature for ventilation, wet-bulb air for evaporative cooling, ground temperature at locations where the soil is cooler than the indoor comfort temperature, and night-sky radiant temperature, which is substantially lower than ambient air in most climates.

Eight US cities (Denver, CO, Los Angeles, CA, Louisville, KY, Madison, WI, Miami, FL, New Orleans, LA, Phoenix, AZ and Washington DC) were selected to represent a range of climate characteristics, including seasonal ambient temperature, diurnal temperature swings, humidity and sky clearness. For each city, an ambient potential to cooling load ratio (ALR) was calculated, with the potential based on an indoor comfort temperature range of 680F – 720F and the load calculated with a base temperature of 650F. Annual ALR, which neglects phase lags between source and load and the associated need for thermal storage, exceeded one for dry-bulb air and for ground temperature for all locations except Miami, New Orleans and Phoenix. Wet-bulb ALR exceeded one for all locations except Miami, and sky ALR exceeded one for all locations. In addition, the effect of limited thermal storage was estimated by calculating daily ALR, which is the sum of the hourly ambient cooling potentials over each 24 hour period, up to a maximum of the daily cooling load on days with cooling loads, divided by the annual cooling load. The annual sum of daily ALR thus approximates the cooling potential of systems with one day’s worth of thermal storage, and has an upper limit of one. The annual sum of daily ALR equaled one for ground temperature for Los Angeles and Madison and for sky temperature for Denver and Los Angeles. The annual sum of daily ground ALR was above 0.9 for all locations except Miami, New Orleans and Phoenix. The annual sum of daily sky ALR exceeded 0.6 for all locations. By utilizing all possible combinations of ambient sources, half of the selected locations attained an annual sum of daily ALR equal to one and the minimum for all locations still exceeded 0.65. A journal article on ambient source cooling has appeared [Robinson & Sharp 2013].

Bench-Scale Experiments – Tests were conducted to measure performance of heat pipes with diameters smaller and larger than the original system. A ¾" heat pipe transferred significantly less energy than the 1" heat pipe used in previous tests. A 1 ¼" heat pipe transferred marginally more energy than the 1" heat pipe. Tests have also been conducted to evaluate night sky radiant cooling panels of design similar to the heat pipe system.

Task 12. Thermochemical Storage for Solar Power – The objective of this task is to study the thermochemical cycles to store solar energy, and to produce electricity from storage. The ammonia cycle $NH_4 \Leftrightarrow N + 2H_2$ was the initial focus of the study. The efficiency of several energy storage cycles used in conjunction with a Stirling cycle engine were compared using TRNSYS. The major finding was that for constant-temperature operating conditions, efficiency depends strongly on recovery of heat in both forward and reverse reactors (Fig. 7).



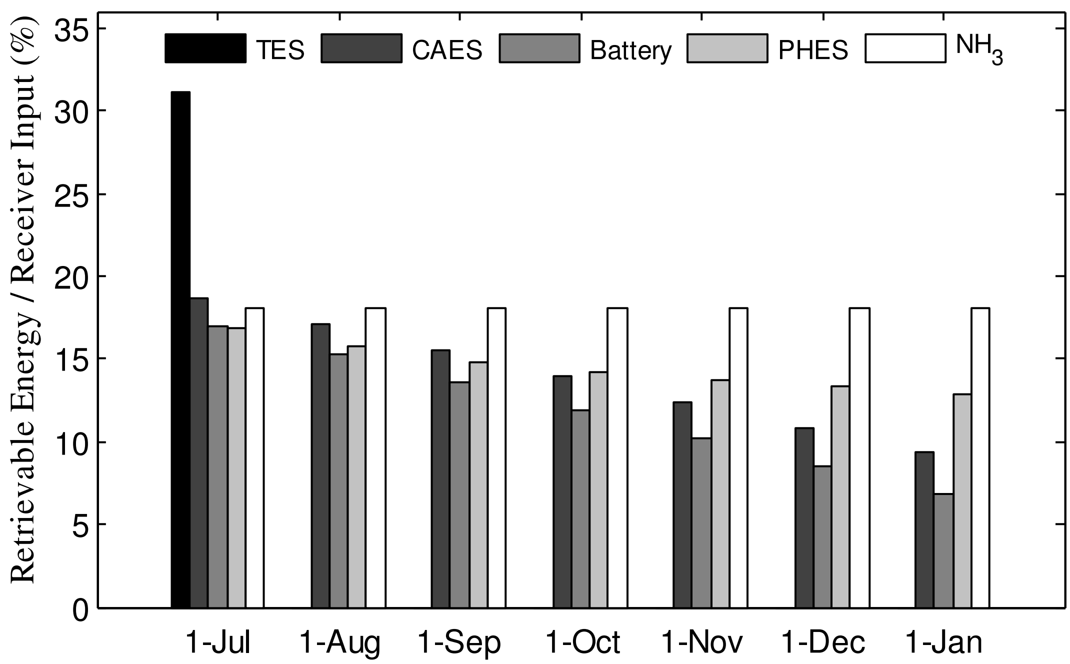
(a) (b)

Fig. 7. Overall (solar-electric-storage-electric or solar-storage-electric) efficiency of the solar driven compressed air energy storage (CAES), battery, pumped hydroelectric storage (PHES) and thermal energy storage (TES) systems as a function of receiver temperature and of the ammonia system as a function of synthesis reactor temperature

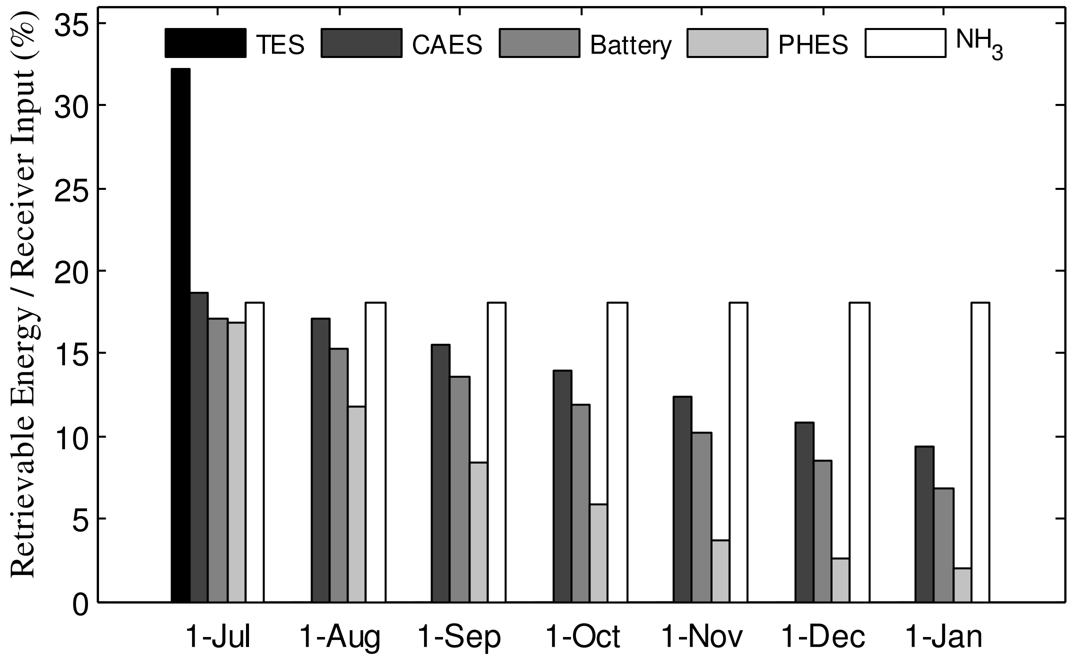
for (a) Louisville, KY and (b) Phoenix, AZ. On both plots, battery efficiency, which was nearly identical to PHES, is hidden by the PHES curve.

The results were compared to competing energy storage mechanisms, such as batteries, elevated hydro, compressed air and sensible heat storage (Fig. 8). Sensible heat storage is most efficient for short periods (hours), but the ammonia cycle is more efficient for long-term storage (weeks). A journal article has appeared on this work [Shakeri, et al. 2014].

Results have recently been obtained on simulating a vanadium chloride cycle that produces hydrogen and chlorine gas $2VCl_3 \rightarrow 2VCl_2 + Cl_2$ and $VCl_2 + HCl_2 \rightarrow VCl_3 + H_2$, which can be used directly in a fuel cell. The HCl fuel cell has higher potential cell voltage and efficiency than H_2O cells, which results in high overall system efficiency. The simulations show higher efficiency than all other storage systems, including TES.



(a)



(b)

Fig. 8. Retrievable energy as a function of time for the five energy storage models in (a) Louisville, KY and (b) Phoenix, AZ.

Task 13. Website Development – A website for the University of Louisville Renewable Energy Applications Laboratory describing these projects funded by DOE was developed. The website is at http://louisville.edu/speed/ulrec.

Task 14. Solar Hot Water System - Burhans Hall. A solar hot water system was installed August-October, 2009 at the University of Louisville's Burhans hall. The system utilizes a drain back configuration, with two 4 by 10 feet collectors manufactured by Alternative Energy Technologies (AE-40) connected to a 120 gallon hot water storage tank in the basement of Burhans Hall. A new 15-gallon, stainless steel tank was installed for drain back storage. The system can generate up to 30,000 Btus of heat and can reduce current natural gas usage for water heating by as much as 50%. The cost of the equipment and installation was approximately $14,000 and the system has a working life of 30 to 40 years. The estimated energy savings is 202 ccf of natural gas annually, or 49% of the current gas demand. The system has been tested by the University and accepted. The system installation is described on the University website at https://louisville.edu/kppc/krec/tech-at-work/solar-hot-water-system-installed-at-shelby-campus.html

Task 15. Additional Tasks to close out the grant - The University has been working with the DOE Project Manager to close out the project grant. In order to meet the University's cost-share requirements and to spend down remaining federal funds, the University has proposed the following demonstration projects, which are under review by DOE.

a. Net Zero Energy Demonstration Homes. A subcontract will be let with the nonprofit Kentucky Highlands Investment Corporation. KHIC's mission is to stimulate growth and create employment opportunities in a 22-county region of Southeastern Kentucky. KHIC is working to build five 1282-square foot homes in Emlyn, Kentucky on a 30 acre tract of land. The homes are designed to be net-zero energy homes. The homes have insulated envelopes, doors, and windows, and energy efficient appliances and HVAC system. The proposed work is to install solar thermal and photovoltaic panels on the roofs of the demonstration homes to off-set energy demands for the homes. The homes are located on Red Witt Rd and Bob Carter Rd in Emlyn, Whitley County, KY 40769. The total estimated cost of this project is $151,680.

b. University of Louisville Student Recreation Center. The Student Recreation Center is currently under construction with a completion date scheduled September 2013. The 128,000 square-foot Center is being constructed on the University's Belknap Campus. The $38 million building is funded by student fees ($98 each semester per student) and private donations. The facility will contain an indoor track, exercise and weight facility, six basketball courts, racquet ball courts, a multi-activity court for indoor soccer and floor hockey, racquetball courts and aerobic studios. Prior to construction the site was a student resident parking lot. The proposed work is to install approximately 15 solar hot water panels, heat exchanger and 500 gallon storage tank to provide domestic hot water for the building. The total estimated cost of this project is $196,293.

c. University of Louisville Natatorium Solar Hot Water Demonstration. The Natatorium not only serves as the men's and women's swimming and diving venue, but also benefits the U of L student body for recreation, fitness and instruction. Construction of the building was completed in 2005 and is located on the University's Belknap Campus. The building is funded through student fees that will eventually provide $7 million towards the complex. U of L students voted in the spring of 1999 to allow $15 of their student fees each semester to be earmarked for the natatorium, with final payment scheduled in 2023. Private donations were also obtained to pay the rest of the building costs. The 1 million gallon pool features an eight-lane, 50-meter competition pool with a depth ranging from 4 feet 6 inches to 18 feet. The 41,000 square foot facility can accommodate up to 800 spectators and athletes. It includes office space, a large meeting/hospitality room and separate locker rooms for the public and for team members. The proposed work is to install approximately 20 solar hot water solar panels and a heat exchanger to preheat water for the existing swimming pool. The total estimated cost of this project is $212,620.

Plans for Next Quarter: Not applicable.

Patents: None.

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9. Robinson BS, Chmielewski NE, Knox Kelecy A, Brehob EG, Sharp MK, “Heating season performance of a full-scale heat pipe assisted solar wall,” Solar Energy 87:76–83, 2013.

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