The Trick to a Twenty-Dollar Utility Bill:
Automating a Solar Climate Control System for Minnesota Climates

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Abstract

This study involved engineering an automation and communications network to control heat flow in a novel solar hydronics system in a Roseville, Minnesota home. The goal of this system was to effectively store enough of the sun's heat during the summer months to heat the home throughout the winter. We installed a Modbus network—the industry standard for RS485 communication—that consists of a master Arduino Mega and five slave Arduino Micro modules. We created software in C/C++ to run 100 temperature sensors, one humidity sensor, and eleven water circulators that direct heat flow to heat-storage components. A unique aspect of the software developed in this study is that it adjusts to time of day, outside temperatures, dew point, humidity, and time of year in order to determine the most effective allocation of the available heat. Final testing of the communications network showed 100% success rate. Because the network can be easily modified or expanded, it is easily applicable to any solar-powered hydronics system.

A) Present Technology

The amount of sunlight that reaches the Earth in just one hour is enough to provide global energy demands for a full year (1); however, efficient and cost-effective technology to capture this energy is just beginning to be developed. An area where solar energy is particularly practical is in residential climate control, which accounted for 22.6% of the total United States energy consumption in 2010 (2). Of the alternative energy sources available, residential solar heating and cooling systems are the most promising because they can be easily installed in pre-existing buildings. Despite these benefits, solar climate control makes up less than 0.05% of all space heating systems and 0.01% of all space cooling systems (3).

A newly developing method of using solar energy for residential climate control is coupling solar technology with hydronic systems. Hydronic heating and cooling has typically been used with geothermal or electric energy systems. In hydronic systems, water flows through an extensive system of tubing to either heat or cool a residence. Applying solar energy to a hydronic system allows for efficient heating and cooling that takes advantage of available energy from the sun. Our technology involved programming Arduino microcontrollers interfacing with a Linux operating system to automate heat flow in a well-insulated laboratory house in Roseville, Minnesota, that has been equipped with a solar hydronic system.

An essential part of an efficient hydronics system is a well-designed control system. The control system is an intelligent network of sensors and computers, which operates the pumps and directs overall flow of heat within the hydronics system. The main objective of the control system is to use available heat in the most efficient way possible, which can be achieved through a series of analytical logic operations. In the past, control systems like this would cost thousands of dollars, but modern technology has made these electronics more available and cost-effective than ever before.

Our technology uses an efficient hydronics system to provide the highest efficiency possible with climate control costs and greenhouse gas emissions at zero. The entire system is designed for climates in places like Minnesota. With hot summers and freezing winters, a significant amount of heat must be stored throughout the non-winter months. Our technology logically decides whether to store heat in long-term storage or short-term storage or distribute heat throughout the house. The system can also be completely run off of low voltage DC power, which is provided by solar panels and batteries. These power sources will continue to run in the event of power outages.

A unique aspect of the software is that it adjusts to time of day, outside temperatures, and time of year in order to make logical decisions about where to distribute heated water from the solar panels. For example, the program directs heat into sand beds in the summer to store heat for winter. On the other hand, the program responds to high indoor air temperature readings by injecting cold water into the hydronic system water to cool the house. By calculating approximate dew points, the program keeps the colder water above the dew point to prevent condensation in the house.

B) History

In the 1970's, The National Aeronautics and Space Administration (NASA) and the United States Department of Energy (DOE) developed some of the first solar-powered hydronics systems. The majority of these systems were only in their prototype phase and rarely taken beyond that. This interest in solar-powered heating systems was sparked by the 1973 oil crisis, and as soon as the oil crisis ended, so did the government's interest in renewable heating systems.

Development in solar-powered hydronics sat dormant until recently. Rising gas prices, significant environmental impact from fossil fuels, and dwindling fossil fuel reserves have people thinking of alternative energy and heating systems. Natural gas is currently the most popular heating method. Although natural gas is a much cleaner fuel than coal or petroleum, over 1.2 billion metric tons of carbon dioxide are emitted every year from natural gas alone (4). According to BP's Statistical Review of World Energy, the world's natural gas reserves will run out in approximately 60 years.

There are three known methods of renewable heating: geothermal, electric from a renewable source, and solar. Electric heating is the least efficient because a great deal of energy is lost in converting electricity to heat (5). Geothermal heating has potential as a renewable residential heating source, but it is very expensive to retrofit existing homes with geothermal since doing so requires deep drilling and is only feasible for new structures (6). Solar heating is efficient and can be installed in most pre-existing buildings. Despite significant benefits, solar heating and cooling systems make up less than 0.05 percent of all space heating systems and 0.01 percent of all space cooling systems (7).

Our technology uses the inexhaustible solar energy from the sun coupled with efficient hydronics system for residential heating and cooling, providing a more efficient and affordable system. The purpose of our study is to program Arduino microcontrollers interfacing with a Linux operating system to automate heat flow in a well-insulated laboratory house in Roseville, Minnesota, that has been equipped with a solar hydronic system.

The laboratory home is equipped with four banks of Solar Skies SS40 4x10 solar panels, three sand beds, drain-back tanks, a 400-gal and an 800-gal water-storage tank, domestic hot water heat exchanger, and in-floor hydronic tubing. The system is currently only partially operable. When the owner of the home wishes to distribute water to a location, he does so manually by operating pumps and valves as needed. This makes operation of the system very limited and somewhat unreliable in its current state.

We installed a network of Arduino microcontrollers and then developed software to run a system of approximately 100 Dallas DS18B20 temperature sensors and 11 Laing D5 Solar 720B circulators that direct heat flow to heat-storage components, solar collectors, and/or hydronic heating system components. Depending on conditional statements set by the temperature sensors, the software sends water from the solar panels into the drain-back tanks, and then, the master controller responds to the temperature sensors to determine which pumps to turn on or off to direct the water to desired locations that include the sand beds, storage tanks, hot water heat exchanger, and/or the in-floor hydronic system.

C) Future Technology

Future development of this technology would make solar-powered hydronics systems even more efficient and consumer-friendly. We predict that one future development will be the ability to run the entire system from a single vertical water tank. The benefit of a vertical tank over a traditional water tank is water stratification. Water stratification occurs when the hotter water is allowed to rise to the top of the tank, and the cooler water sinks to the bottom. The control system can then measure the temperature of the water at different points in the tank,and remove water in areas which satisfy the systems demonstrated temperature requirement. Vertical water tank hydronics systems have been used before but have never been run completely off of solar energy. A single vertical water tank would greatly reduce the amount of area the system takes up within the home, making solar-powered hydronics systems more appealing to those who are concerned about the system intruding into their living space.

Heating systems should be something that takes place in the background, without being too visible. Smaller, more efficient solar collectors will hide the heating system from view, boosting the aesthetic appeal of this technology. New reflective materials and optical configurations could magnify the sun's energy, thus eliminating the need for a multitude of large, bulky solar collectors. Advancement in the solar-collector field would take years of design and testing. Some universities, like Uppsala University, are currently conducting research in this field.

Further developments in insulating materials could be applied to this system to increase the storage efficiency. New materials such as Silica Aerogel or the Airloy X100 could be used to line the edges of the storage tanks and prevent energy from escaping through the air or ground. Vacuum insulated panels, although difficult to build, would provide maximum insulation to the water storage tanks. The current insulation material, high-density extruded expanded polystyrene (XPS), provides about 0.9 square-meter kelvin per watt, whereas Silica Aerogel provides 1.76 square-meter kelvin per watt, and Vacuum Insulated Panels provide 5.28-8.8 square-meter kelvin per watt. These new materials would allow solar energy to be stored for a very long time without losing heat.

In addition to improvements to the insulating materials, improvements to solar thermal materials could also greatly benefit solar hydronics. The current system uses only sensible heat thermal storage. Some experimental thermal storage systems also use phase change heat or latent heat. These heat storage methods store heat when a certain material melts or solidifies. Latent heat storage can improve the storage efficiency by approximately 3 percent and can reduce the container size by up to 60 percent. The University of California, Jet Propulsion

Laboratory and select industry partners are currently pioneering research in this field.

Currently, the use of solar hydronics is very limited as to where systems can be installed. The Arctic and Antarctic regions receive little or no sunlight during the coldest months of the year. For regions like this, an extremely efficient storage system is needed. Solar hydronics has never been tested in these regions but it is likely that this technology does not yet exist.

In the next twenty years, it is likely that many more solar hydronic heating systems will be functioning. In the next fifty years, due to scarcity of fossil fuels, solar-powered hydronics systems may be one of the most prominent heating systems on the market. With widespread use of this technology, initial installation costs would plummet, making it an even more desirable choice for the average consumer. It is, however, still a young technology, and much more research can be done to improve the system.

D) Consequences

Retrofitting solar-powered hydronics systems to existing buildings have a number of positive consequences. Compared to traditional forced-air systems, hydronics systems cost less to operate, are more efficient, and offer more customizable features than other sources of energy. Because solar-powered hydronics systems are extremely efficient and rarely need addition of water into the system, costs to operate them are minimal. Additionally, because the specific heat of water is so high, water can convey almost 3,500 times as much heat as the same volume of air, making solar-powered hydronics systems far more efficient than forced-air systems. Hydronic systems also require less than 10% of the electrical energy of forced-air systems and do not lose significant amounts of heat, whereas forced-air systems lose significant amounts of heat through air stratification (8). Furthermore, power companies, such as Xcel Energy Inc., offer incentives like rebates, rewards, and credit for excess energy generation in some states to those who install photovoltaic solar panels further decreasing costs of this system. (9) Because of increased efficiency and utilization of solar energy, these systems are environmentally friendly by significantly decreasing greenhouse gas emissions (10).

Further benefits of solar-powered hydronics systems are that they are customizable. Piping can be installed in walls, floors, ceilings, roofs, or others places where heating or cooling is desired. Hydronics function by heating spaces, pools, and domestic hot water, melting snow off surfaces, or even heating surfaces, such as artificial turf, that are difficult to heat with other methods. Solar-powered hydronics systems can also be divided easily into zones to customize temperatures. For example, a garage may be kept at a lower temperature than a zone in the house. These customizable features should make hydronics systems more desirable to consumers.

Widespread use of solar hydronics systems will also have negative consequences. The use of solar energy is currently intermittent. Although systems of the future will be able to store significant amounts of heat through use of hydronics, those technologies are just developing; therefore, Today, solar power is not as reliable as other sources of energy because they do not collect heat on cloudy days.

Another negative of the aspect of solar hydronics systems is their appearance. Some feel that the aesthetics of solar collectors are not ideal for some homes, as they do not fit traditional styles of architecture. However, careful design and future development of organic photovoltaics (OPVs) that are flexible so can be wrapped onto any surface or incorporated into traditional roofing shingles should cause greater acceptance to this technology (11).