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ABSTRACT

This paper outlines the design of an active solar thermal loop system that will be integrated with an air source heat pump hot water heater to provide highly efficient heating of a water/propylene glycol mixture. This system design uses solar energy when available, but reverts to the heat pump at night or during cloudy weather. This new design will be used for hydronic heating in the Applied Energy Laboratory, a teaching laboratory at Purdue University, but it is more generally applicable for a residential scale system that could be used for both hydronic heating and hot water production. This combined system should provide efficient heating at a fraction of the operating costs of competing electric, gas, or even heat pump water heaters. The initial cost of installing a similar system is currently relatively high, but it should be noted that the design is still in the prototype stage. The price should reduce dramatically when the system is commercialized. There are multiple applications where the production of heated fluid by a combined solar/heat pump hydronic system can be much more attractive than conventional heating methods. Construction and implementation of this proposed design will take place summer of 2014 and data collection will be pursued afterwards.

1. INTRODUCTION

The costs of energy and resources have consistently been increasing. Since 2003, energy costs have increased by 30% in the United States and are predicted to continue to increase indefinitely (U.S. Energy Information Administration, 2014). In Indiana, Duke Energy recently received approval for a 16% rate increase for all its residential customers (Wilson, 2014). Due to this rapid increase, the economics for net-zero buildings that are self-sufficient in terms of their annual energy demand from utilities has become more favorable. One key feature when developing net-zero performance is discovering a way to produce hot water or heat more efficiently using less energy. The average small building has a traditional Heating, Ventilation and Air-Conditioning (HVAC) and a hot water system that uses electricity or natural gas. These traditional systems use a lot of energy, and better options are available.

Since the cost of energy is continually increasing, heat pumps are a great way of saving energy when it comes to heating. Heat pumps allow for energy savings due to the fact that they use ambient thermal energy. For example, an air source heat pump hot water heater absorbs ambient heat from the air and then transfers that absorbed energy through a refrigerant to a storage tank. The heating energy for a heat pump is electricity for a compressor and a small circulation motor so air can flow across the refrigerant. A basic thermodynamic analysis shows that an air source heat pump is three times more efficient than a conventional electric water heater (BPA, 2014). In other words, a heat pump delivers three times as much heat at the same cost as an electric water heater.

The combination of solar thermal energy with a heat pump to maximize efficiency and reduce energy costs has been studied for a long time. One of the first systems to utilize both solar thermal and a heat pump was a solar-assisted heat pump (SAHP). This theory was researched in the 1950's by Sporn and Ambrose (1955). This theory utilizes the solar collectors as the evaporator and achieves a higher Coefficient of Performance (COP) (Sporn and Ambrose, 1955). This theory since has been researched and further investigated, using different techniques to develop more efficient designs and systems.

Chaturvedi and Shen (1984) evaluated the performance of a direct expansion SAHP. This system builds off of the conventional SAHP by using the same concept, but a refrigerant is used rather than using air or water as a working fluid. Also, the collector and evaporator functions were combined into one. These various changes allowed for better thermal performance due to direct expansion and evaporation of the refrigerant in the collector. Changing the working fluid to a refrigerant simplifies the design and also aids freeze protection through the system (Chaturvedi and Shen, 1984).

Rather than just using the solar panels as an evaporative heat source for the heat pump, Panaras, Mathioulakis and Belessiotis (2013) took a different approach. The approach taken was to combine both the solar thermal collectors and the heat pump in parallel rather than series and not allow them to physically interact. This means that the solar panels supply heat to the storage tank, as well as the having heat pump add additional heat when needed. The storage tank in this system is filled with water and the collectors' added heat by a coil heat exchanger located in the tank. Heat added by the heat pump is done through an external water to refrigerant heat exchanger. The main scope of this work was the assessment of the energy saving potential of the systems compared to an electric or direct fired system, which seemed to provide a significant energy savings based on their conclusions (Panaras *et al.*, 2013).

The research being pursued for this project is focusing on an active loop solar thermal system that has been integrated with an air source heat pump. This system builds on and differs from the literature in several aspects. This new design will allow the systems to work in series, but both the solar collectors and the heat pump water heater will add their own additional heat to the storage tank unlike a SAHP system. Also, the system will be circulating a working medium of a 50/50 mix of water and propylene glycol for freeze protection.

The evaluation of this design will be based on comparing the baseline performance of the current system to the solar heat pump system. The baseline data will use electrical resistance for heating. The end goal of the heat pump assisted solar thermal system is to reduce energy use by a significant amount. Comparison of the baseline to the updated system will be done by recording manual data, constructing calculations, and monitoring the system performance through a direct digital control platform (DDC).

2. SYSTEM DESIGN

2.1 System Overview

Figure 1 is a schematic of the solar thermal system that utilizes an integrated heat pump hot water heater as a back-up heat source. The main components of the system are a main circulating pump, solar panel array, heat exchanger, and an integrated heat pump hot water heater. The main circulating pump is the heart of the system that keeps the fluid flowing to all of the components. It circulates a 50/50 water/propylene glycol mixture to optimize heat transfer and provide freeze protection. The solar collectors are the primary source of heating, but the heat pump will provide additional heating capacity when needed. The heat exchanger allows for domestic water heating and also allows the system to dump extra solar thermal heat that may be produced when it is not needed. An expansion tank is a key safety feature for this system, allowing for safe thermal expansion on the transfer medium.

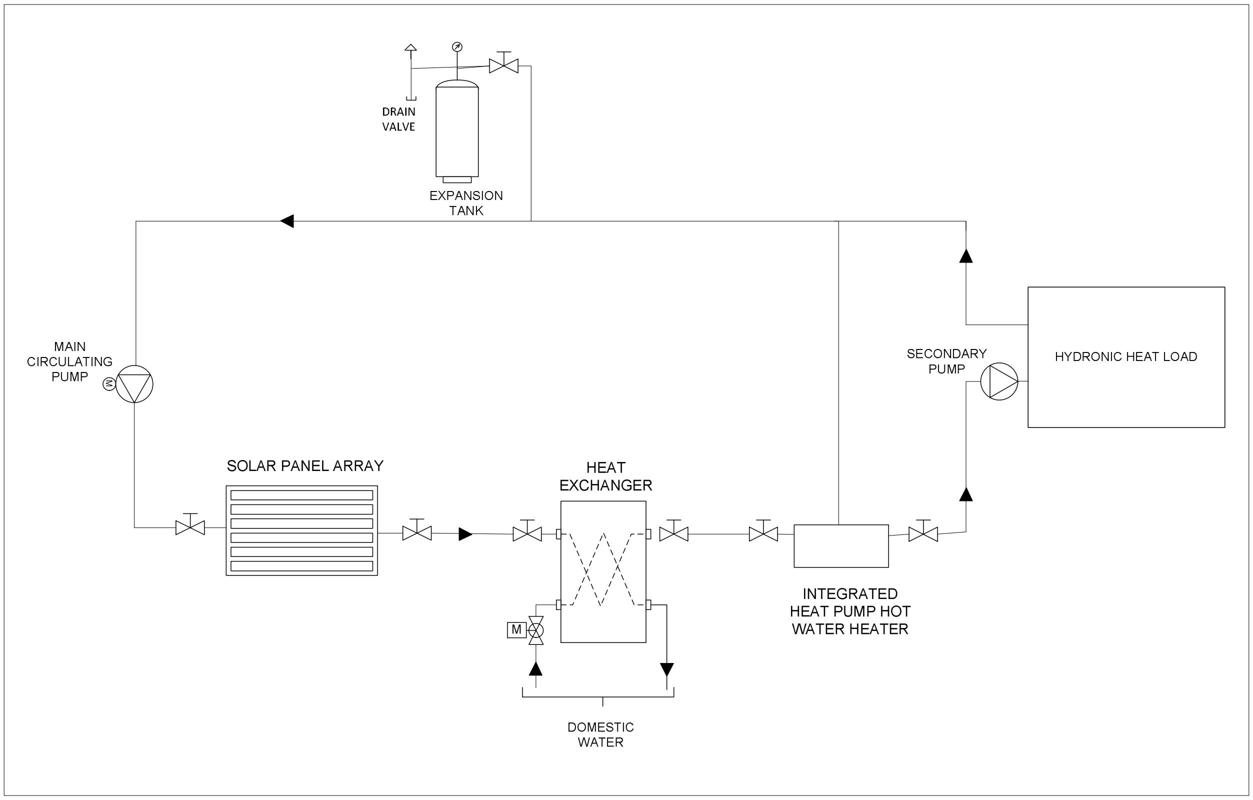

Figure 1: Schematic of solar heat pump hot water generation system.

The piping is designed as a primary/secondary loop system. The primary loop consists of the main circulating pump, the solar thermal panel array, the heat exchanger, the integrated heat pump hot water heater, and the expansion tank. The water/glycol mixture is heated in this primary loop. A secondary loop contains the hydronic heating load. The secondary loop draws the heated water/glycol mixture from the heat pump to meet the demands of the hydronic heating load. The fluid is circulated through the heating load and returned to the primary loop. A secondary pump is used in this loop to maintain the necessary flow rate and pressure in the secondary loop.

The components are located to maximize space and efficiency. The solar panels are located on the roof of Knoy Hall, while the air handling unit, heat exchanger, and heat pump hot water heater are all located in a conditioned space inside the lab. The area being conditioned by the equipment is separate from the area in which the components are located. This means that while the heat pump of the system is pulling air from a conditioned space, it is still separate from the zone that it is conditioning.

2.2 System Operation

There are three basic modes of operation based on the weather conditions. The first mode is a strictly solar powered mode. This means that the solar collectors are producing enough thermal energy to meet the demands of the load. In solar only mode, the heat pump hot water heater and internal heating elements will not be used, therefore saving large amounts of electrical energy.

The second mode is a combination of both the solar collectors and the heat pump hot water heater. This mode will be used when the collectors are producing some heat, but not enough to meet the load request. This mode allows the glycol mixture to pass though the solar collectors and collect as much heat as possible, then circulate though the heat pump hot water heater to gain the extra heat needed. With the glycol mixture circulating though the heat pump hot water heater, the electric heating elements are able to turn on if both the solar collectors and heat pump do not meet the demand. The combined mode uses a little more energy, but still saves a significant amount of energy relative to pure electrical operation.

The third and final mode is strictly heat pump hot water heater mode. When the weather is cloudy or it is night, the collectors will be bypassed to allow the air source heat pump hot water heater to supply the full demand amount. This mode will use the most amount of energy, but will continue to be efficient due to the favorable coefficient of performance for a heat pump cycle which collects energy from ambient air.

Figure 2 shows the solar thermal collectors being used within this design. This figure shows a total of 9 collectors, but the collectors that will be utilized in this design will be the first 4 from the left, which are flat solar thermal panels and also the evacuated heat pipe, which is on the far right. The remaining panels, that will not be used, use air as a transfer medium. Overall, a total of 5 solar thermal collectors will be utilized for this proposed design.

Figure 2: Solar thermal collectors on the roof of Knoy Hall

Currently, the design phase for the solar thermal heat pump hot water heater project has been completed and the system will be installed in the summer of 2014. Once installed, the data collection can begin and the system can be analyzed for its applied performance.

3. DESIGN PERFORMANCE

The design of this system allows a single transfer fluid to move throughout the entire system for hydronic or domestic water heating. By utilizing two heat sources, a large amount of heat can be generated to meet the demands on the system.

3.1 Solar Potential

The capability of the existing solar thermal system was estimated from solar insolation data collected over decades by recording the average value of clear solar insolation. Equation 1 below shows the calculation for obtaining the daily kWh potential from the solar thermal system. The collector area is calculated using 4 main collectors at 1.6m^2 and a single heat pipe collector with an area of 1.28m^2. This gives a total area of 7.7m^2. The collector efficiency is given by the solar thermal panel manufacturer.

Two locations were chosen to present how the system may perform in different climates. Insolation data was collected from NREL's Redbook for the Indianapolis, IN area (Marion and Wilcox, 1994, pp. 84) and for Atlanta, GA (Marion and Wilcox, 1994, pp. 62). Using Equation 1, Table 1 shows the average monthly solar potential for Indianapolis.

$$Q = Isolation\left(\frac{kWh}{m^2}\right) * Collector\ Area\ (m^2) * Collector\ Efficency \tag{1}$$

As shown in Table 1, the total annual kWh availability for a comparable sized system is ~7700 kWh. Daily usage averages around 21 kWh.

Table 1: Indianapolis, IN kWh Solar Potential

Solar Insolation ($kWh/m^2/day$)		Daily kWh Potential	Monthly total kWh potential
January	3.1	14.32	444
February	3.9	18.01	504
March	4.4	20.32	630
April	5.1	23.56	707
May	5.6	25.86	802
June	5.8	26.79	804
July	5.8	26.79	830
August	5.7	26.33	816
September	5.3	24.48	734
October	4.5	20.78	644
November	3.1	14.32	430
December	2.6	12.01	372
Average	4.6	21.13	
Total annual kWh availability:			7717

Table 2 shows the annual solar kWh potential for the warmer climate of Atlanta is ~8600 kWh, with an average daily kWh potential of 23.5 kWh. Tables 1 & 2 help illustrate that the solar resource varies by geographic location and must be accounted for during the design phase.

Table 2: Atlanta, GA kWh Solar Potential

Solar Insolation ($kWh/m^2/day$)		Daily kWh Potential	Monthly kWh total potential
January	3.8	17.55	544
February	4.6	21.25	595
March	5.3	24.48	759
April	5.8	26.79	804
May	5.8	26.79	830
June	5.8	26.79	804
July	5.7	26.33	816
August	5.7	26.33	816
September	5.4	24.94	748
October	5.2	24.02	745
November	4.2	19.40	582
December	3.7	17.09	530
Average	5.1	23.48	
Total annual kWh availability:			8572

3.2 Heat Pump Potential

The air source heat pump hot water heater used in this system is able to supply 5000 BTU/hr, or 1.46 kilowatts. If the assumption is made that the heat pump hot water heater can run 12 hours a day, a total of 17.5 kWh can be obtained. Annually, this amounts to 6400 kWh.

3.3 Combined Potential

By adding the kWh rate from the heat pump to the output of the solar thermal system in Indianapolis, a total of 14000 kWh can be realized from the entire system for thermal use. By multiplying the total thermal energy amount by an efficiency factor of 0.9 for the heat exchanger, the thermal potential for domestic water heating with the combined solar heat pump system can be found. The efficiency factor is an average estimate of this particular type of heat exchanger. The total kWh available to heat domestic water is 12700 kWh annually. Calculating the total combined system potential for the warmer climate of Atlanta produces 15000 kWh of total thermal energy and 13400 kWh for domestic water heating.

3.4 Geographical Consumption vs. Potential

According to the EIA (2009), the East North Central (ENC) area, including Illinois, Indiana, Michigan, Ohio, and Wisconsin, the average household uses 16% of their total annual electrical usage on water heating. The EIA also shows that average annual total household energy consumption is around 150 million BTUs or 44000kWh (U.S. Energy Information Administration, 2009. *Household Energy Use in Illinois*). Using these numbers, it can be deduced that the average household in the ENC area uses around 24 million BTUs or 7000 kWh annually for water heating. The 12700 kWh available from the system is well above the 7000 kWh demand for the ENC area.

The warmer climate of the South Atlantic region was again chosen to observe the differences in the continental United Sates. According to the EIA (2009), the average annual household energy usage for water heating was 17%. The average annual total household energy consumption is around 75 million BTUs or 22000 kWhs (U.S. Energy Information Administration, 2009. *Household Energy Use in Georgia*). Calculating for the South Atlantic area yields an average household energy usage of around 12.75 million BTUs or 3700 kWh annually for water heating.

Again, with a combined heating potential of 13400 kWh from the combined solar heat pump hot water heater system, this covers the domestic hot water demand by over 4 times.

4. DESIGN ECONOMICS

The economics of a heat pump assisted solar thermal system is determined largely by the installed cost. An average cost for a basic solar thermal system was found to be around $5,000 after taxes and incentives are factored in (Walsh, 2014). The system used to estimate costs has two panels, each 4ft (1.22m) by 6ft (1.83m), along with an 80 gallon (300 liter) storage tank. The designed system will replace the storage tank with a 55 gallon (210 liter) air source heat pump hot water heater, and add ~72% more panel area (4.4m vs 7.7m). Based on the additional panels required and the additional cost for the heat pump hot water heater, a reasonable estimate of the total cost of the designed system is $6,000. This system's life is expected to be at least 20 years.

To achieve a reasonable payback, this system should only be installed in a location where there is a need for significant heat on a year round basis. One option would be a small manufacturing enterprise that has a year round need for process heating. Another option would be a residential or small commercial setting where the system could provide both hot water and hydronic space heating. A third option that will be investigated using this laboratory prototype is a commercial building, where the heat could be used during the summer months to provide reheat air for an hair handling unit. In other words there could be some economic benefits for a heat pump assisted solar thermal system that provides hot water and space heating in the winter as well as hot water and reheat for space dehumidification during the summer.

5. CONCLUSIONS

The proposed design for a combined solar thermal system with a back-up heat pump hot water heater is feasible in certain situations. The economics will improve over time due to the increasing cost of energy.

The goal of this research is to move this technology forward and be ready to take advantage of changes that will happen in the near future. As one example, the United States Environmental Protection Agency is moving forward with plans that limit carbon emissions on a state by state basis with a goal of a 30% nationwide reduction using 2005 as a baseline. Achieving this goal means shifting away from cola fired power plants and towards heat pumps and solar thermal systems that are more benign in terms of their impact on the environment.

Building codes are also trending towards requiring a certain amount of renewable energy capability in the buildings to meet high efficiency building standards. Section 7.3.2 of ASHRAE 189.1 (Heating, R. a., 2011) states that "*Building project* design shall show allocated space and pathways for future installation of on-site renewable energy systems and associated infrastructure that provide the annual energy production equivalent of not less than 6.0 kBtu/ft^2 (20 kWh/m^2) for single-story buildings and not less than 10.0 kBtu/ft^2 (32 kWh/m^2) multiplied by the total *roof* area in ft^2 (m^2) for all other buildings." The combined solar heat pump hot water heater system can be a strong candidate for meeting these ever improving building standards. Also, the appeal to a company and the individual to have renewable and sustainable energy associated with them must not be discounted. The combined solar heat pump hot water heater system is able to meet the needs and the desires of the consumers while providing being a reliable source of thermal energy.

REFERENCES

(1) Chaturvedi, S. K., & Shen, J. Y. (1984). Thermal Performance Of A Direct Expansion Solar-assisted Heat Pump. *Solar Energy*, *33*(2), 155-162.

(2) Panaras, G., Mathioulakis, E., & Belessiotis, V. (2013). Investigation of the performance of a combined solar thermal heat pump hot water system. Solar Energy, 93, 169-182.

(3) Sporn, P., Ambrose, E.R., The heat pump and solar energy, in: Proceedings of the World Symposium on Applied Solar Energy, Phoenix, Arizona (1955), pp. 159-170.

(4) Wilson, C.D. (2014, March 19) *Court Gives Duke Energy Go-Ahead for Rate Increase*. Retrieved from http://www.theindychannel.com/news/local-news/court-gives-duke-energy-go-ahead-for-rate-increase.

(5) BPA - Energy Efficiency | Heat Pump Water Heaters. (n.d.). *BPA - Energy Efficiency | Heat Pump Water Heaters*. Retrieved March 26, 2014, from http://www.bpa.gov/energy/n/HPWH.cfm

(6) U.S. Energy Information Administration - EIA - Independent Statistics and Analysis. (2014). *Short-Term Energy Outlook*. Retrieved March 25, 2014, from http://www.eia.gov/forecasts/steo/report/electricity.cfm.

(7) U.S. Energy Information Administration - EIA. (2009). *Household Energy Use in Georgia* [Data file]. Retrieved March 25, 2014, from http://www.eia.gov/consumption/residential/reports/2009/state_briefs/pdf/ga.pdf.

(8) U.S. Energy Information Administration - EIA. (2009). *Household Energy Use in Illinois* [Data file]. Retrieved March 25, 2014, from http://www.eia.gov/consumption/residential/reports/2009/state_briefs/pdf/il.pdf.

(9) Marion, W. F., & Wilcox, S. (1994). *Solar radiation data manual for flat-plate and concentrating collectors* (pp. 84). Golden, Colo.: National Renewable Energy Laboratory.

(10) Marion, W. F., & Wilcox, S. (1994). *Solar radiation data manual for flat-plate and concentrating collectors* (pp. 62). Golden, Colo.: National Renewable Energy Laboratory.

(11) M.P. Walsh (personal communication, April 02, 2014)

(12) Heating, R. a. (2011). *Standard for the design of high-performance green buildings: except low-rise residential buildings.*. (pp. 23). Atlanta, GA: American Society of Heating, Refrigerating, and Air-Conditioning Engineers.