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An innovative hybrid photovoltaic thermal heat pump system for houses

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ABSTRACT

This paper presents the simulation of a hybrid photovoltaic/thermal (PV/T) heat pump system used for single-family houses. The system consists of PV/T collectors, a water-to-water heat pump, an outdoor swimming pool, and pumps. A radiant floor system is used to provide space heating and cooling. Six different operational modes are considered according to space air temperature, the PV/T collector temperature, and the swimming pool water temperature. Depending on the operation modes, the energy source/sink side of the heat pump can be connected to either PV/T collectors or the outdoor swimming pool. The outdoor swimming pool acts as thermal storage, which is charged by the PV/T collectors when space conditioning is not needed. TRNSYS energy simulation software package is used to model the system. Simulation results for a single-family house located in Baltimore, MD showed that the proposed system saved more than 50% annual energy consumption relative to a reference air-source heat pump system.

1. INTRODUCTION

Buildings are major energy consumers in the world. For example, in the U.S., buildings account for 40% of the national total primary energy use and residential buildings contribute 53% of the buildings sector energy consumption (EIA 2018). Among different energy end uses in residential buildings, space heating and cooling contribute about 48% of total delivered energy consumption (EIA 2013). Because of the considerable amount of energy consumption for residential heating and cooling, it is important to seek for innovative systems that integrate solar energy for the design and operation of residential buildings (Cutler 2013).

The concept of using photovoltaic (PV) modules for electricity generation and solar collectors for heating generation is well known and widely used. Combining both technologies results in hybrid photovoltaic/thermal (PV/T) collectors, which can be rack-mounted or integrated with building envelope. Meanwhile, there is increasing use of heat pumps in residential building in recent years. Coupling PV/T collectors and a heat pump (HP) together is potentially favorable for both PV and HP operation. The PV electrical efficiency improves because of the reduced module temperature. The HP efficiency improves because of the boosted evaporator temperature. Therefore, many studies combined solar systems with heat pumps for the development of solar assisted heat pump (SAHP) systems (Bakker *et al*. 2004). However, the majority of studies on SAHP systems focused on the use of PV/T collectors only as the heat source for heat pump's heating generation (Hailu *et al*. 2015). Kamel *et al*. (2014) studied a system that coupled building integrated PV/T collectors with an air-source heat pump (ASHP). Warm air from the PV/T collectors acted as the ASHP's heating source. The system was simulated in the winter conditions of Toronto, Canada. It was found that their system, including selling the surplus renewable electricity generation, could reduce the electricity bill by $500 per year. The HP seasonal coefficient of performance (COP) was also increased from 2.74 to 3.35. In a subsequent study (Kamel *et al*. 2015), they improved the system design by adding a thermal storage tank. The storage tank was charged at daytime and was discharged at nighttime to preheat the source-side air to the ASHP and they could save 20% of the HP electricity consumption during winter and the HP seasonal COP was increased to 3.45. Li *et al*. (2015) developed and implemented a PV/T-HP system to heat an open plan office space at Purdue's Living Laboratory. The building integrated PV/T collectors were used to preheat the ventilation air and warm up the air circulated to an air-to-water heat pump, which provided hot water for radiant floor heating. Their simulation studies showed that using PV/T collectors led up to 45% total energy saving including the electricity generation by the PV panels compared to the baseline operation of radiant floor heating.

In most previous PV/T-HP related studies, space cooling was provided by dedicated components such as absorption chiller (Calise *et al*. 2016a), cooling tower (Calise *et al*. 2012, Calise *et al*. 2016b), ground surface water piping system (Zhang *et al*. 2016), and ground source heat pumps (Entchev *et al*. 2014, Xia *et al*. 2017), which made the system design and operation much complicated. However, PV/T collectors can be potentially used for cooling generation based on the radiative cooling concept. Radiative cooling represents a thermal process that a hotter body loses heat to a cooler body through long-wave radiation heat transfer. This means that PV/T collectors when exposed to the sky with a low temperature will lose energy and may end up with a below-ambient surface temperature, thereby becoming a cooling source.

Eicker and Dalibard (2011) studied radiative cooling of PV/T collectors and systems based on experiments and simulation. They simulated night radiative heat exchange of PV/T collectors with the sky using TRNSYS. After validating the simulation results with an experiment apparatus, they applied the system in a residential zero energy building in Madrid. The cooling power contributed by PV/T collectors was between 60 to 65 W/m^2 when being directly used by phase change material (PCM) in ceiling and 40 to 45 W/m^2 when cooling a warm storage tank. Pean *et al*. (2015) investigated the nighttime radiative cooling potential of unglazed PV/T solar collectors using both numerical models and experiments. Based on the experimental measurements at the Technical University of Denmark, they found that the tested PV/T collectors had cooling capacity in the range between 20 and 75 W/m^2 in summer. Later, they modeled and experimentally measured a system integrating PCM panels and PV/T collectors. In the system, the cold water from PV/T collectors charged PCM ceiling panels at night and the charged ceiling panels worked as radiant panels when the space needed cooling at daytime (Bourdakis *et al*. 2016).

To the authors' knowledge, very few studies have investigated both the heating and cooling potential of PV/T collectors. Palla *et al*. (2014) investigated the potential of using PV/T collectors for space heating, cooling, and electricity production in six different locations. Based on the TRNSYS simulation, they concluded that the highest radiative cooling potential can be achieved in cold and moderate climates where cooling is temporarily required. Fiorentini *et al*. (2015) combined PV/T collectors with PCM thermal storage unit for a net-zero energy house. The system operated in both winter and summer taking advantage of daytime solar radiation and nighttime radiative cooling. In the heating season, daytime solar radiation on the PV/T collector was used to warm up the fresh air circulated through the collectors while in the cooling season, radiative cooling of the collectors was used to cool down the fresh air. After heating or cooling, the fresh air was supplied either to the space directly if ventilation was needed or to the PCM for thermal storage.

This paper intends to investigate the potential of using PV/T collectors as both the heat source and the heat sink depending on the heat pump's operation mode and use radiant floor system for space conditioning. The reminder of this paper is organized as follows. The PV/T-HP system is presented in Section 2 with an emphasis on its components and controls. A hypothetical house and a baseline system are described sequentially in Sections 3 to set up the context for the proposed system performance evaluation. TRNSYS simulation models are briefly discussed in Section 4. Simulation results are discussed in Section 5. The paper ends with some conclusions and suggestions for future work.

2. PV/T-HP SYSTEM DESCRIPTION

Figure 1 shows the schematic diagram of the proposed PV/T-HP system. The main system components include PV/T collectors, a water-to-water heat pump, an outdoor swimming pool, and water circulation pumps. The PV/T collectors are used to generate electricity and collect (or dissipate) thermal energy for heating (or cooling). Because the paper focuses on the system thermal performance, only heating and cooling are discussed here. Glycol solution is the heat transfer medium used to collect (dissipate) thermal energy through the PV/T collectors. The heated (cooled) glycol solution can be circulated to the heat pump or to the swimming pool via a heat exchanger. The swimming pool functions as a large thermal storage tank. The water-to-water heat pump provides hot water or cold water for the radiant floor system used for space conditioning. The heat pump's source side can connect to the PV/T collectors or the swimming pool via the heat exchanger and the load side is connected to the radiant floor system.

Six modes are considered to control the system operation according to the space temperature, the PV/T collector temperature, and the pool water temperature. These six modes are based on an actual project that won the 2017 Innovative Energy Project award from the Association of Energy Engineers (https://www.sundrumsolar.com/), but with some simplifications.

- Mode 1: PV/T-HP for heating. This mode is activated when 1) the house thermostat calls for heating, and 2) the PV/T collector temperature is higher than 5.6°C. The PV/T collector temperature can be understood as the glycol solution outlet temperature. In this mode, glycol liquid flows from the PV/T collector to the source side of the heat pump; the heat pump runs to provide hot water to the radiant floor.
- Mode 2: Pool-HP for heating. This mode is activated when 1) the house thermostat calls for heating, 2) the PV/T collector temperature is lower than 5.6°C, and 3) the pool water temperature is higher than 1.7°C. In this mode, the system operates similarly to Mode 1 except that the source side of the heat pump connects to the pool via a heat exchanger.
- Mode 3: Pool water heating with PV/T. This mode is activated when 1) it is in the heating season (Nov. 1 to March 31); 2) the house thermostat does not call for heating; and 3) the PV/T temperature is 8.3°C higher than the pool water temperature. Once initiated, this mode continues until the temperature difference between the PV/T collector and the pool water falls below 2.2°C. In this mode, glycol liquid flows through the PV/T collector to heat up pool water via the heat exchanger.
- Mode 4: PV/T-HP for cooling. This mode is activated when 1) it is nighttime (i.e., 8:00 pm to 6:00 am), 2) the house thermostat calls for cooling, and 3) the PV/T collector temperature is less than 32.2°C. In this mode, the system operates similarly as Mode 1 except that the heat pump runs for cooling and provides cold water to the radiant floor system.
- Mode 5: Pool-HP for cooling. This mode is activated when 1) the house thermostat calls for cooling, and 2) the PV/T collector temperature is higher than 32.2°C. In this mode, the system operates similarly as Mode 2 except that the heat pump runs for cooling and provides cold water to the radiant floor system.
- Mode 6: pool water cooling with PV/T. This mode is activated when 1) it is not in the heating season (April 1 to Oct. 31), 2) the house thermostat does not call for cooling and heating, and 3) the PV/T collector temperature is 5.6°C lower than the pool water temperature. Once initiated, this mode continues until the temperature difference between the pool water and the PV/T collector falls below 2.2°C.

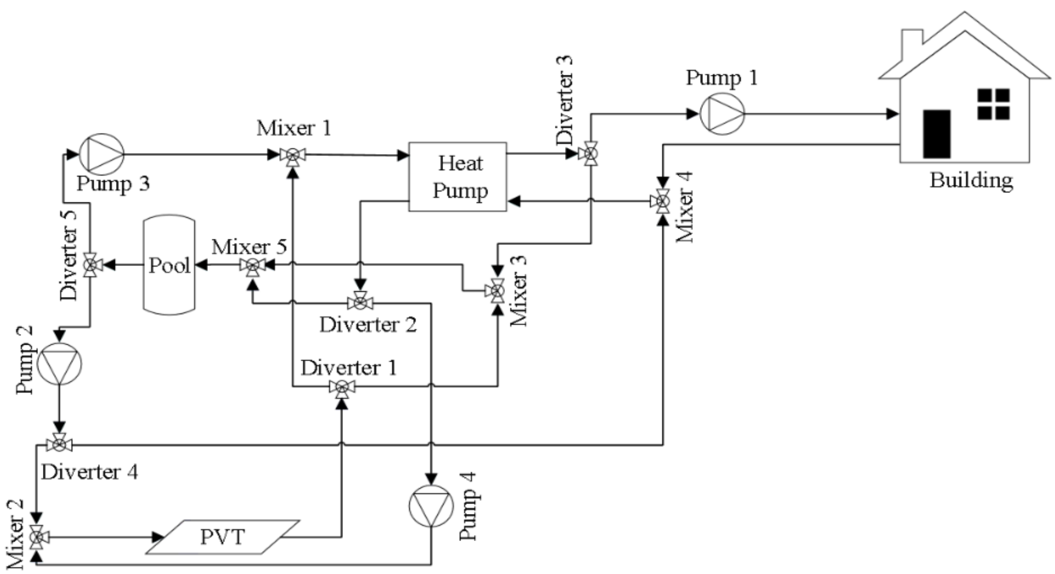

Figure 1: Schematic diagram of the proposed PV/T-HP system

3. HOUSE AND REFERENCE SYSTEM DESCRIPTION

A hypothetical single-family house in Baltimore, MD was used to study the energy performance of the PV/T-HP system described in Section 2. The house has one floor with a total area of 200 m^2. It has a rectangular shape with an aspect ratio of 0.86. The house has a flat roof with a floor-to-ceiling height of 2.44 m. Slab-on-grade floor and wood-frame constructions are assumed. On each façade, windows occupy 2 m^2. The swimming pool has a volume of 100 m^3. PVT collectors with the slope of 45° on the roof occupy an area of 39 m^2. Table 1 lists the thermal performance of exterior building envelope that satisfies the residential code requirement (IECC 2006).

To facilitate the evaluation of the proposed system performance, a conventional air-source heat pump system is used as a reference.

Table 1: thermal performance of exterior building envelope

Building Envelope	**Thermal Performance**
Roof	U factor=0.170 W/m^2K
Ground Floor	R value=1.942 m^2K/W
Exterior Walls	U factor =0.465 W/m^2K
Windows	U factor =1.69 W/m^2K SHGC=0.66

4. TRNSYS SIMULATION

TRNSYS is the software used to model and simulate the PVT-HP system, the reference system and the house. TRNSYS was selected because it has a rich library of validated built-in components for renewable energy systems in buildings. In TRNSYS, parameters such as energy, mass flows and temperatures can be calculated for each component during simulation time and integrated over the desired time period.

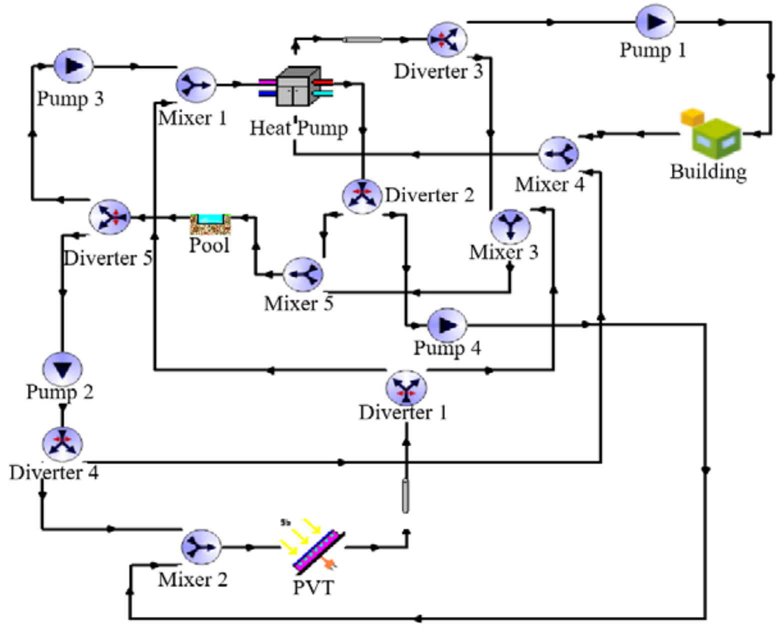

Figure 2: TRNSYS model

Figure 2 illustrates the model developed in TRNSYS. In comparison with Figure 1, the following needs to be noted:

- Water instead of glycol solution is modeled as the liquid circulating the PV/T collectors although freezing protection must be considered in the field. Because of this simplification for simulation, the heat exchange is not modeled.
- Diverters and mixers are used in the TRNSYS simulation wherever three-way valves are needed in the physical piping network. The diverter's control signal defines the path of water flow.

Table 2 lists the major components, the corresponding TRNSYS Types, and their key parameter settings in the simulation. Auxiliary simple components such as pipes, flow mixers and diverters, controllers, printers, and integrators are not listed for the sake of brevity. As Table 2 shows, Type 563 is used to model unglazed PV/T collectors in this work. The collectors have solar absorptivity of 0.9, emissivity of 0.8, absorber plate thickness of 2 mm, and absorber thermal conductivity of 51 W/m-K, all of which are from Xia (2017). The water-to-water heat pump and air-source heat pump are all sized according to the space peak loads, which are found through a pre-run of annual simulation to be 8700 W for heating and 2500 W for cooling. The water-to-water heat pump efficiency, both at rated full load conditions and part-load conditions, are based on a 3-ton (10500 W) commercial product from Water Furnace. For the supply fan used in the reference model, it has a total efficiency of 0.38 and a static pressure of 400 Pa, which was chosen to meet 0.5 w/cfm requirement per IECC (2006). The air flow rate was calculated based on the rated coil capacity and the desired air temperature difference (11°C) across the coils. The residential code requirement (Amrane *et al*. 2010) is referred to set the air-source heat pump's cooling and heating efficiency to 14 SEER and 8.2 HSPF respectively. It should be noted that internal heat gain was not modeled in this simulation study.

Table 2: TRNSYS components and their main parameters

Component	**TRNSYS type**	**Main Parameters**
PVT Collector	563	Area = 39 m^2 Absorptivity = 0.9 Emissivity = 0.8 Absorber plate thickness = 0.002 m Thermal conductivity of the absorber = 51 W/m.K Number of water tubes = 150 Outer diameter of water tube = 0.02 m
Pool	344b	Volume = 100 m^3 Height = 1.8 m Area = 55.6 m^2 Cover thickness = 0.005 m Cover emissivity = 0.6 Cover absorption coefficient = 0.6
Water-to-water Heat Pump	927	Rated heating capacity = 10027 W Rated COP = 4.8 Rated cooling capacity = 5264 W Rated EER = 15.5 Btu/W.h Rated source and load flow rates = 1363 Kg/hr
Pump	114	Water flow rate = 1363 Kg/hr Rated power = 15 W
Fan	146	Air flow rate = 2570 m^3/hr Rated power = 756 W
Air-source Heat Pump	119	Rated Heating capacity = 10027 W HSPF= 8.2 Btu/W.h (Rated COP = 3.4) Rated total cooling capacity = 5264 W Rated sensible heat ratio = 0.75 SEER= 14 Btu/W.h (Rated EER = 12 Btu/W.h)

TRNSYS Type 56 was used to model the house. Both inside and outside convective heat transfer coefficients of building envelope were dynamically calculated considering wind speed, orientation, and surface temperature. Ground temperature was calculated by TRNSYS Type 77. Air infiltration was calculated by TRNSYS Type 75b assuming the house has 10 air change per hour at 50 Pa. The house has a heating set point of 21°C and a cooling set point of 26°C.

5. RESULTS AND DISCUSSION

The simulation was performed with one-minute time step using the typical meteorological year weather data of Baltimore, MD. Three representative days, one for winter, one for summer, and one for shoulder, were selected to verify the system operation by illustrating the operation mode changes and the temperature profiles of selected components. In addition, based on the simulation results, the proposed PV/T-HP system and the conventional air-source heat pump system were compared regarding their energy consumption in different seasons and across the whole year.

5.1 Representative day analysis

Figure 3 shows the system operation on January 11th, a selected representative day of winter. Figure 3a shows the operation mode, the space temperature in the house (T_{space}), the outdoor air temperature (T_{OA}), the PV/T collector temperature ($T_{collector}$), and the pool water temperature (T_{pool}). Figure 3b shows the water inlet and outlet temperatures of the radiant floor ($T_{radiantIn}$ $T_{radiantOut}$) and the floor temperature (T_{floor}).

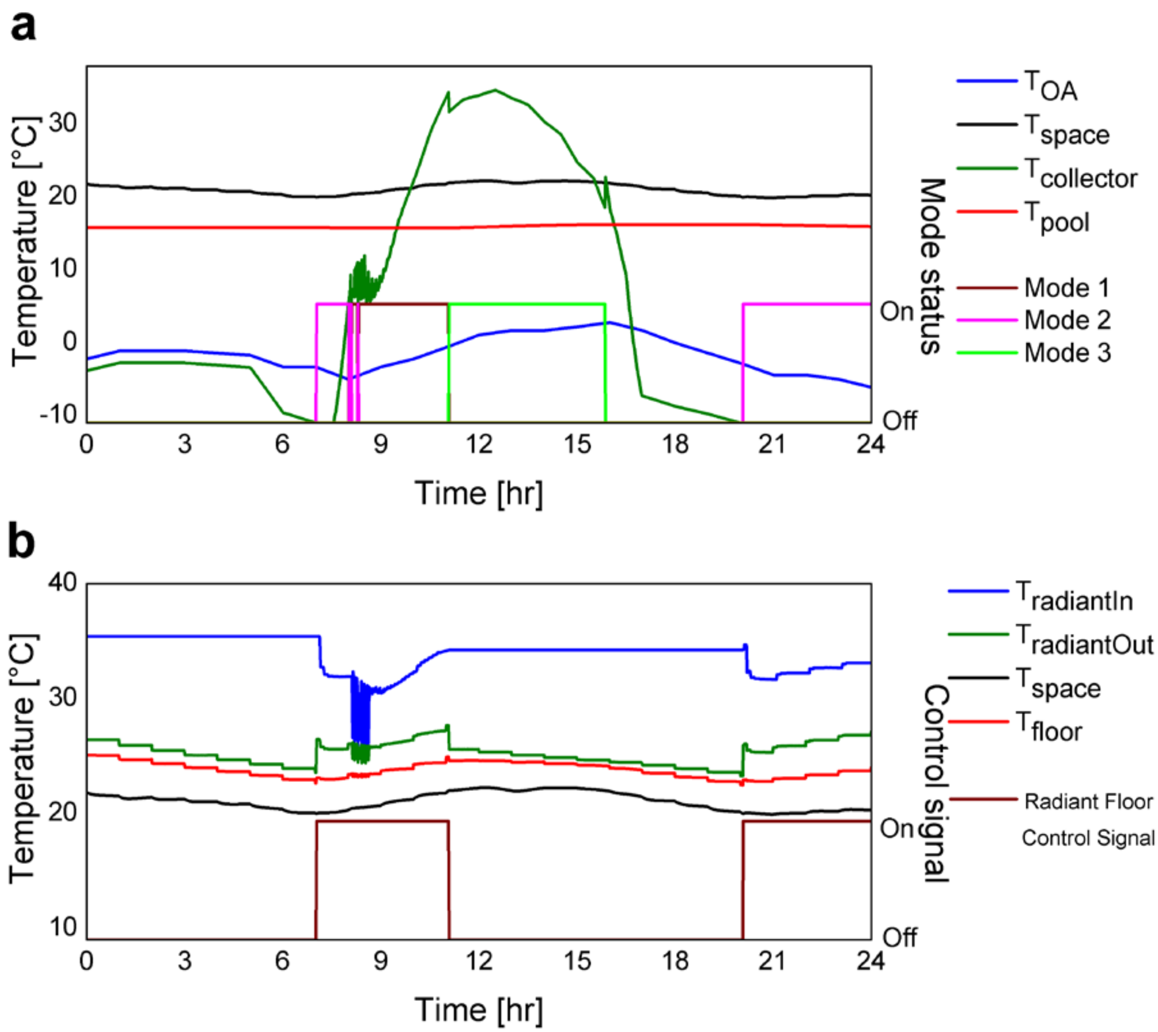

Figure 3: System operation on January 11th **a)** Operational modes and related temperatures **b)** Radiant floor system temperatures

Figure 3 indicates the following:

- All three possible winter operation modes are observed, and the system operates as expected according to the applied control logics. The space temperature, which is 21.9°C at the beginning of the day, is reduced until it reaches 20°C at 7 am and the house thermostat calls for heating. Mode 2 (pool-HP for heating, see Section 2) is activated because the PV/T collector temperature is low. At around 8 am, the PV/T collector temperature increases to be higher than 5.6°C. Therefore, Mode 1 (PV/T-HP for heating) is used for space heating until 11 am when the space temperature reaches 22°C. From 11 am until 4 pm, Mode 3 (pool water heating) is activated because the space does not call for heating, but the collector temperature is 8.3°C higher than the pool water temperature. None of the modes is used for 4 hours until space heating is needed, and Mode 2 is the operating mode from 8 pm to the end of the day.
- Because of the large thermal mass, the pool water temperature has minor changes across the whole day. The pool temperature decreases from 15.9°C to 15.8°C in the morning when the pool is used as the source side of the heat pump operation (Mode 2). In the middle of the day, the pool water temperature increases

from 15.8°C to 16.3°C as a result of PV/T heating pool water (Mode 3). At the end of the day, the pool water temperature decreases to 16°C because of Mode 2 operation.

- The space temperature fluctuates between 20°C and 22°C because of the use of 2°C temperature deadband around the heating set point at 21°C.
- The water temperature in the radiant floor system remains below 35°C and the floor temperature changes between 23°C and 25°C, which lies in the acceptable range considering occupants' comfort.
- Although the outdoor air temperature peaks at about 2.8°C, the PV/T collector temperature is higher than 10°C for most of the daytime, which leads to high heating efficiency of the heat pump.

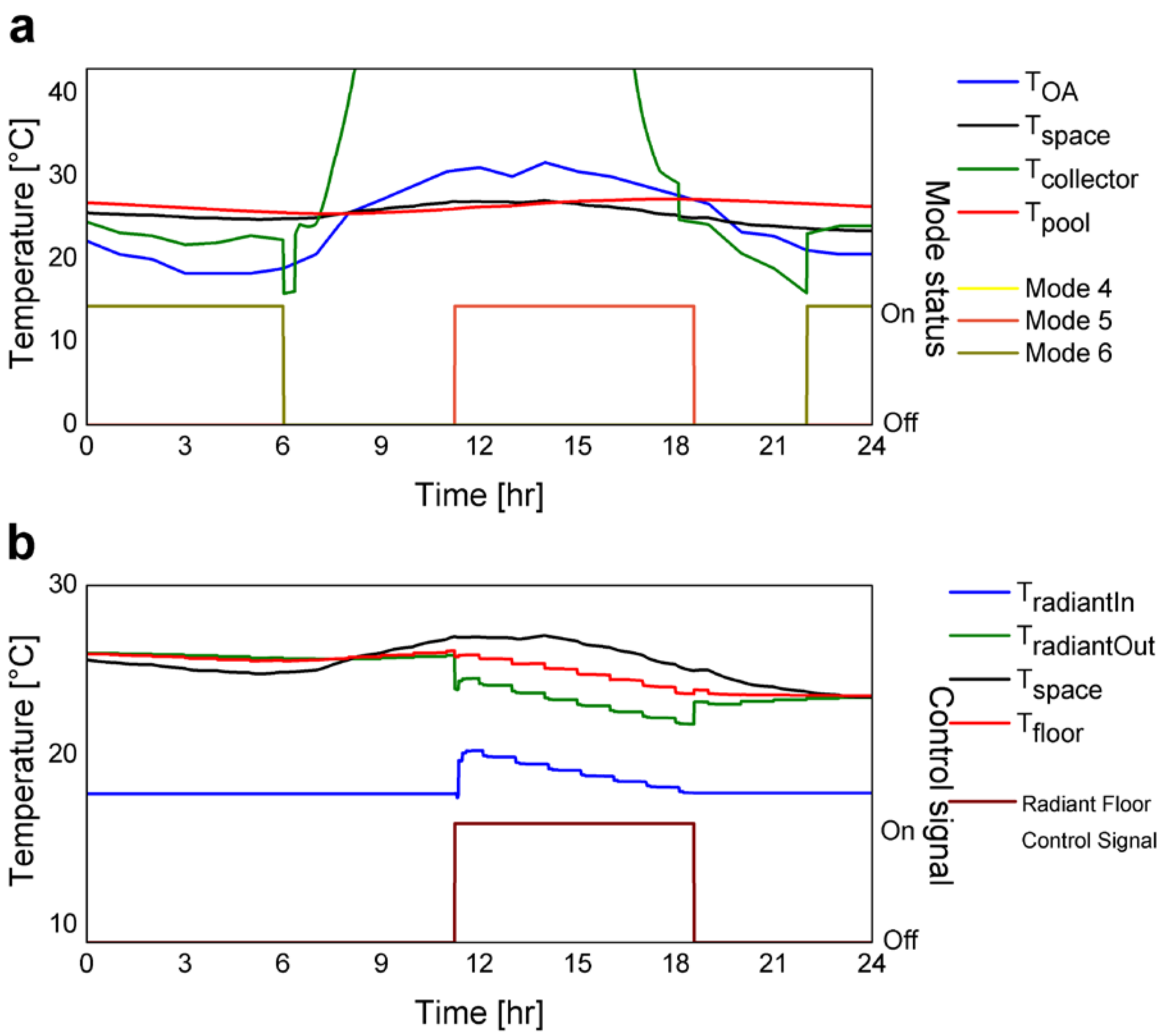

Figure 4: System operation on July 28th **a)** Operational modes and deciding temperatures **b)** Radiant floor system temperatures

Figure 4 shows the system operation on July 28th, a selected representative summer day. This figure indicates the following:

- Two of the three possible operation modes are observed, and the system operates as expected according to the applied control logics. From midnight to the early morning of the day, Mode 6 (pool water cooling, see Section 2) is used because the house thermostat does not call for cooling and the PV/T collector temperature is 5.6°C lower than the pool water temperature. In the afternoon, Mode 5 (pool-HP for cooling) applies when the space calls for cooling because the PV/T collector temperature is higher than 32.2°C, and the pool water is used on the source side of the heat pump operation for cooling. The day ends with Mode 6 as the pool water is cooled by the PV/T collector. Mode 4 (PV/T-HP for cooling) is not activated in this representative day because this mode's conditions (see Section 2) are not met anytime during this day.

Similar to the winter representative day, the pool water experiences minor temperature changes around 23°C because of the large thermal mass. The pool water temperature experiences more changes compared to the winter representative day because the pool cover is removed. It is reduced from 26.8°C to 25.6°C during early hours of the day when the pool is cooled by the PVT collector (Mode 6). The water temperature is then increased during the day and it experiences the 1.2°C increase when the pool is used as the source side of the heat pump operation (Mode 5) and the water temperature is reduced again at night to 26.4°C.

- The water temperatures in the radiant floor are above 17°C and the floor temperature is between 24°C and 26°C.

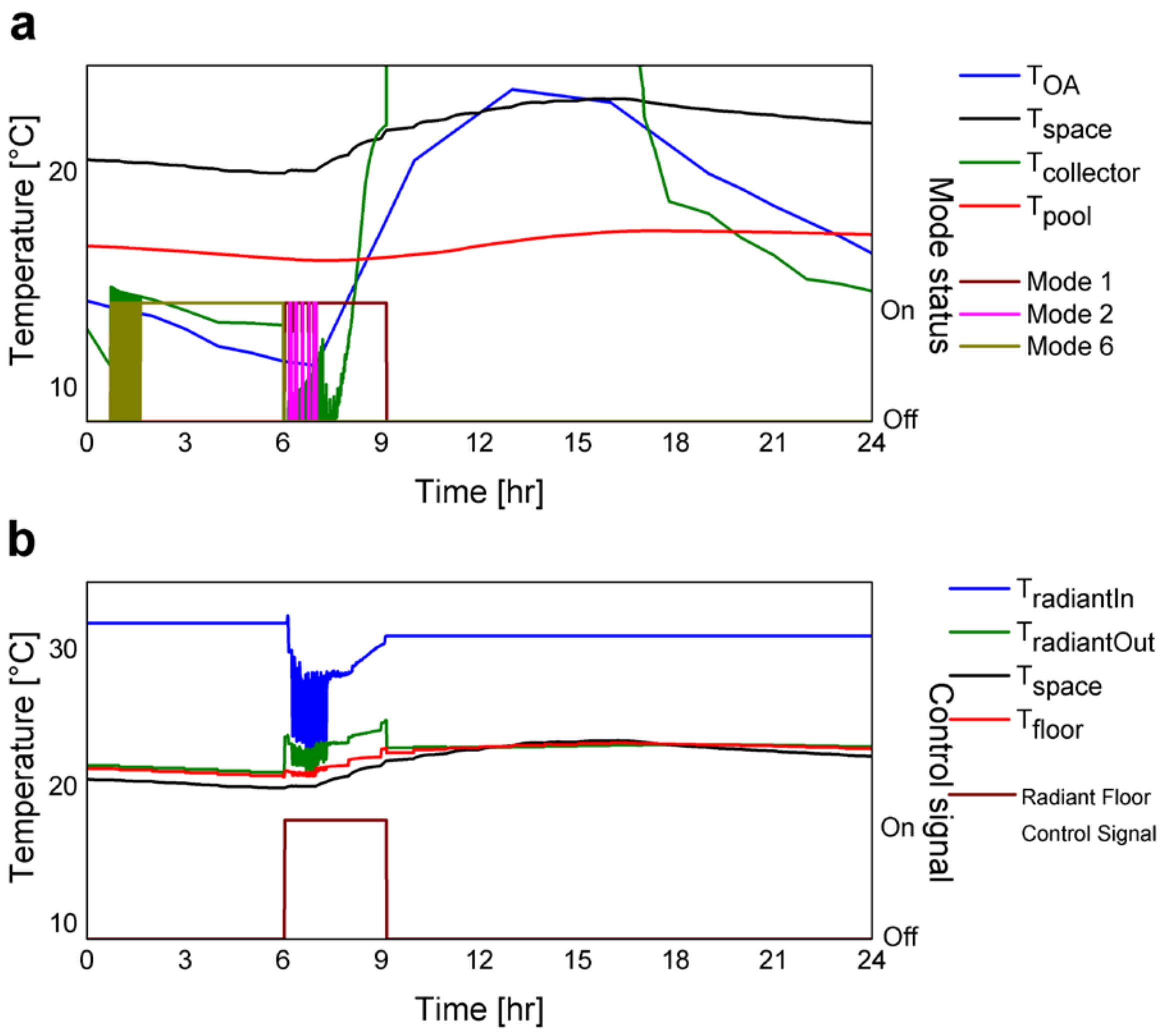

Figure 5: System operation on October 1st **a)** Operational modes and deciding temperatures **b)** Radiant floor system temperatures

The system operation on October 1st, a representative day of shoulder seasons, is shown in the figure 5. This figure indicates the following:

- The PVT collector cools the pool through night time radiative cooling (Mode 6) during early hours of the day until the house thermostat calls for heating and the PVT collector is used for space heating (Mode 1).
- Similar to the winter representative day, the pool water experiences minor temperature changes around 17°C because of the large thermal mass.
- The water temperature in the radiant floor stays below 32°C and the floor temperature is between 21°C and 23°C, which is in the acceptable range.

5.2 Energy Consumption comparison

In addition to the three representative days, we ran the simulation for both the proposed and the reference systems in January, July, October, and the whole year. These three months are selected to understand the system performance in winter, summer, and shoulder months. Figure 6 shows the results that compares the onsite energy consumption between the two systems. For the proposed PV/T-HP system, the energy consumption comes from the pumps and the water-to-water heat pump while for the reference system, the energy consumption comes from the fan, and the air-source heat pump. Figure 6 leads to the following observations:

- The proposed system is more efficient than the reference system during the winter, summer, and shoulder months. Specifically, the proposed system consumes 37%, 44%, and 70% of the reference system energy consumption, respectively in January (winter month), July (summer month), and October (shoulder month). The efficiency is mostly due to the increased (decreased) water temperature on the source side of the heat pump operation during heating (cooling).
- For the whole year, the proposed PV/T-HP system consumes 48% of annual energy consumption of the reference system. This percentage is closer to the average percentage of energy consumption in the heating months because the modeled house has much higher heating loads than cooling loads.

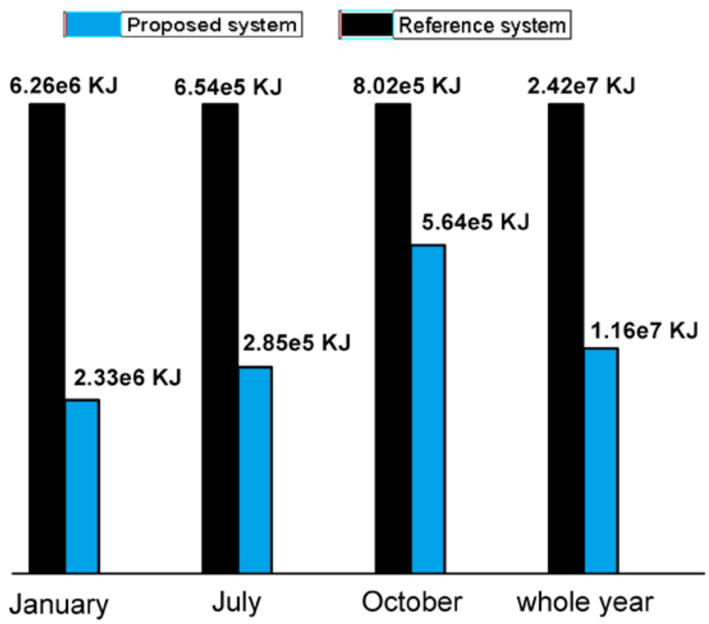

Figure 6: Onsite energy consumption comparison between the reference and proposed systems

6. CONCLUSIONS

This study used TRNSYS simulation to evaluate the performance of a system that comprises water-based PV/T collectors, a water-to-water heat pump, and an outdoor swimming pool. This hybrid PV/T-HP system provides hot water (or cold water) to meet the space air conditioning needs. The source side of the heat pump connects to either the PV/T collectors or the pool depending on the operating conditions. The pool water acts as thermal storage, which is charged by collectors through daytime solar radiation or nighttime radiative cooling. The simulation was run for a 200-m^2 single-family house in Baltimore, MD. Based on the simulation results, the proposed system saved 63%, 56%, and 30% onsite energy consumption of the reference air-source heat pump system, respectively in January, July, and October. For the whole year, the proposed system is 52% more efficient than the reference system. Several avenues for further improvement of the research are envisioned as follows: 1) The positive impact on PV power generation needs to be estimated; 2) domestic hot water production via PV/T collectors or heat pump desuperheater needs to be explored; and 3) system performance needs to be verified via experimental studies or field tests.

REFERENCES

Amrane, K., Nadel, S., Sachs, H. (2010). The regional standards agreement for residential furnaces, air Conditioners, and heat pumps: process, results, and implications. *ACEEE Summer Study on Energy Efficiency in Buildings*, 24-35.

Bakker, M., Zondag, H. A., Elswijk, M. J., Strootman, K. J., & Jong, M. J. M. (2005). Performance and costs of a roof-sized PV/thermal array combined with a ground coupled heat pump. *Solar energy*, *78*(2), 331-339.

Bourdakis, E., Péan, T. Q., Gennari, L., & Olesen, B. W. (2016). Daytime space cooling with phase change material ceiling panels discharged using rooftop photovoltaic/thermal panels and night-time ventilation. *Science and Technology for the Built Environment*, *22*(7), 902-910.

Calise, F., d'Accadia, M. D., & Vanoli, L. (2012). Design and dynamic simulation of a novel solar trigeneration system based on hybrid photovoltaic/thermal collectors (PVT). *Energy conversion and management*, *60*, 214-225.

Calise, F., d'Accadia, M. D., Figaj, R. D., & Vanoli, L. (2016a). A novel solar-assisted heat pump driven by photovoltaic/thermal collectors: Dynamic simulation and thermoeconomic optimization. *Energy*, *95*, 346-366.

Calise, F., d'Accadia, M. D., Figaj, R. D., & Vanoli, L. (2016b). Thermoeconomic optimization of a solar-assisted heat pump based on transient simulations and computer Design of Experiments. *Energy conversion and management*, *125*, 166-184.

Cutler, D. S. (2013). *Improved modeling of residential air conditioners and heat pumps for energy calculations*. University of Colorado at Boulder.

EIA. (2013) U.S. Energy Information Administration. 2013. *2009 Residential Energy Consumption Survey* – Table CE3.1 Household Site End-Use Consumption in the U.S., Totals and Averages.

EIA. (2018) U.S. Energy Information Administration. *Monthly Energy Review* – Table 2.1 Energy Consumption by Sector-2015 data.

Eicker, U., & Dalibard, A. (2011). Photovoltaic–thermal collectors for night radiative cooling of buildings. *Solar Energy*, *85*(7), 1322-1335.

Entchev, E., Yang, L., Ghorab, M., & Lee, E. J. (2014). Performance analysis of a hybrid renewable microgeneration system in load sharing applications. *Applied Thermal Engineering*, *71*(2), 697-704.

Fiorentini, M., Cooper, P., & Ma, Z. (2015). Development and optimization of an innovative HVAC system with integrated PVT and PCM thermal storage for a net-zero energy retrofitted house. *Energy and Buildings*, *94*, 21-32.

Hailu, G., Dash, P., & Fung, A. S. (2015). Performance evaluation of an air source heat pump coupled with a building-integrated photovoltaic/thermal (BIPV/T) system under cold climatic conditions. *Energy Procedia*, *78*, 1913-1918.

IECC (2006). *International Energy Conservation Code* (IECC). International Code Council, Inc.

Kamel, R. S., & Fung, A. S. (2014). Modeling, simulation and feasibility analysis of residential BIPV/T+ ASHP system in cold climate—Canada. *Energy and Buildings*, *82*, 758-770.

Kamel, R., Ekrami, N., Dash, P., Fung, A., & Hailu, G. (2015). BIPV/T+ ASHP: technologies for NZEBs. *Energy Procedia*, *78*, 424-429.

Li, S., Joe, J., Hu, J., & Karava, P. (2015). System identification and model-predictive control of office buildings with integrated photovoltaic-thermal collectors, radiant floor heating and active thermal storage. *Solar energy*, *113*, 139-157.

Palla, N., Braun, R., Jobard, X., Mitina, I., Cremers, J., & Eicker, U. (2014). Development of Multivalent PV-Thermal Collectors for Cooling, Heating and Generation of Electricity. In *International Plea Conference* (Vol. 30, No. 2014, pp. 16-18).

Péan, T., Gennari, L., Olesen, B. W., & Kazanci, O. B. (2015). Nighttime radiative cooling potential of unglazed and PV/T solar collectors: parametric and experimental analyses. In *Proceedings of the 8th Mediterranean Congress of Heating, Ventilation and Air-Conditioning (CLIMAMED 2015)*.

Xia, L., Ma, Z., & Kokogiannakis, G. (2017). Performance Simulation of a Ground Source Heat Pump System Integrated with Solar Photovoltaic Thermal Collectors for Residential Application.

Zhang, S., Zhuang, Z., Hu, Y., Yang, B., & Tan, H. (2016). Applicability Study on a Hybrid Renewable Energy System for Net-Zero Energy House in Shanghai. *Energy Procedia*, *88*, 768-774.