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Simulated Performance of a Photovoltaic Thermal Heat Pump System for Single-family Houses

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Abstract

This paper presents the design, operation and performance simulation of a hybrid photovoltaic/thermal (PV/T) heat pump system targeted for single-family houses. The proposed system consists of PV/T collectors, a water-to-water heat pump, an outdoor swimming pool, pumps and a forced air system for space conditioning. Using water as the heat transfer medium, the PV/T collectors are used to collect solar energy in the heating season and to dissipate energy to the sky via radiative cooling in the cooling season. The heated or cooled water from PV/T collectors can be 1) used as the heat source/sink of the water-to-water heat pump, which then provides hot or cold water to the water coils in the air handler for space conditioning; or 2) used to charge the swimming tool, which acts as the thermal storage and connects to the heat pump as needed on the source side. There are a total of six different operational modes, the operation of which depends on the space air temperature, the PV/T collector temperature, and the swimming pool water temperature. The system performance was simulated with TRNSYS software. Preliminary results showed that the proposed system saved 30% annual energy consumption relative to a reference air-source heat pump system.

Keywords: *PV/T, Heat Pump, Radiative Cooling, Energy Saving*

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1. Introduction

Buildings consume about 40% of the total primary energy in the U.S., more than a half attribute to the residential sector (EIA 2018). Regarding energy end uses, space heating and cooling accounts for 48% of the energy consumption in residential buildings (EIA 2013). Therefore, it is important to develop innovative space heating and cooling systems that can minimize energy consumption from nonrenewable resources. In this regard, a solar assisted heat pump system that combines photovoltaic/thermal (PV/T) collectors and a water-to-water heat pump (HP) has the advantage of efficiency improvement for both components. Such hybrid systems were explored by different research groups as potential efficient design solutions for energy savings in residential buildings (Nejma et al. 2013). In literature, most PV/T-HP studies focus on using PV/T collectors only as the heat source for heat pump's heating generation (Hailu et al. 2015, Li et al. 2015). As noted by Eicker and Dalibard (2011) and Bourdakis et al. (2016), PV/T collectors can also be used for radiative cooling, a process in which long wave radiation is used to transfer heat from a hotter body to a cooler body, by taking advantage of very cold outer space at night to achieve below-ambient temperatures for the PV/T collectors. However, there is only very limited work on investigation of both the heating and

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cooling potential of PV/T collectors (Palla et al. 2014, Fiorentini et al. 2015).

This paper intends to add some knowledge to the PV/T-HP systems by investigating the potential of using PV/T collectors as the heat source and sink of a HP when combined with an air-handling unit for space conditioning. The paper is organized as follows: The proposed PV/T-HP system and its operational modes are presented in Section 2, where the baseline system for performance comparison is also discussed. Then, the hypothetical house is described in Section 3. Section 4 covers TRNSYS simulation with a focus on TRNSYS Types for different components. Section 5 presents preliminary simulation results, which mainly include system operation analysis in selected days of different seasons (i.e., winter, summer, and shoulder seasons) and annual energy savings of the proposed system in comparison with the baseline system. The paper ends up with some conclusions and recommendations for future work.

2. Proposed PV/T-HP system and baseline descriptions

The proposed PV/T-HP system includes PV/T collectors, a water-to-water heat pump, an outdoor swimming pool, water circulation pumps, and an air handler that supplies conditioned air to the space for heating and cooling. The air system includes a cooling coil, a heating coil, and a fan as shown in Figure 1. PV/T collectors can be used to generate electricity and collect thermal energy. Because the paper has a focus on the thermal performance of the system, we do not consider PV/T collector's electricity generation in the current stage. In this system, the swimming pool functions as a massive thermal storage and the water-to-water heat pump provides hot water or cold water to the water coils for air conditioning. Water is used as the heat transfer medium to collect or dissipate thermal energy through the PV/T collectors. The heated (or cooled) water can be circulated to the heat pump or to the swimming pool. The source side of the heat pump can connect to the PV/T collectors or the swimming pool while the load side connects to the water coils in the air handler.

The reference system that is used for energy consumption comparisons and energy savings potential of the proposed system is a split air-source heat pump system.

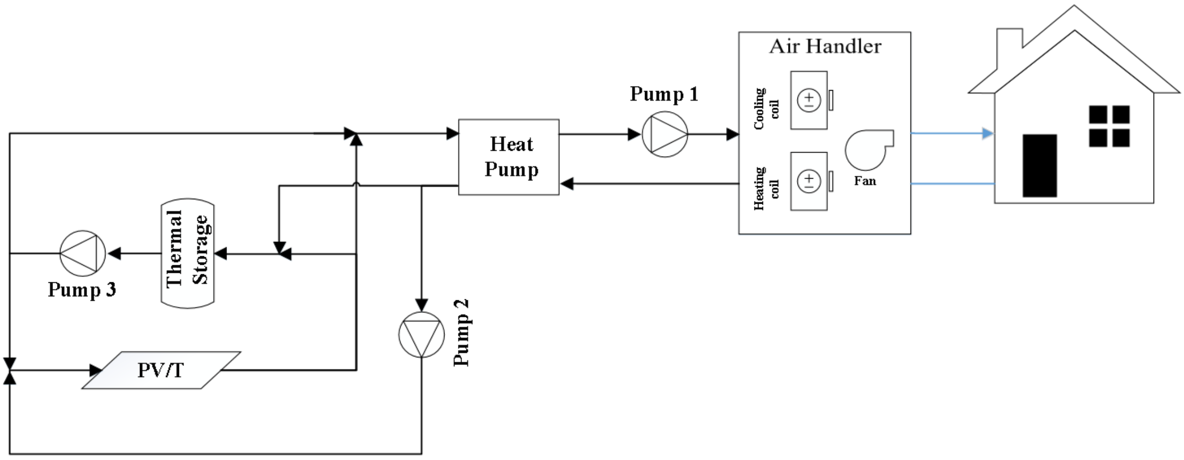

Fig. 1: Schematic diagram of the proposed PV/T-HP system

Six modes are considered for the proposed system operation. Major parameters used to determine the operating mode include space temperature, the PV/T collector temperature, and the pool water temperature. These six modes and their underlying rules are mainly from the 2017 Innovative Energy Project awarded by the Association of Energy Engineers (https://www.sundrumsolar.com/). Some simplifications were made to exclude the domestic hot water heating and backup space heating modes. Table 1 summarizes the system operational modes and the associated control strategies.

These six operating modes are divided into heating modes (Mode 1, 2, and 3) and cooling modes (Mode 4, 5, and 6). In Mode 1 (PV/T-HP for heating), water flows from the PV/T collector to the source side of the heat pump; the heat pump runs to provide hot water to the heating coil of the air hander; and the fan in the air handler runs to supply heated air to the house. In Mode 2 (Pool-HP for heating), the source side of the heat pump is connected to the pool and the rest of connections are similar to Mode 1. In Mode 3 (Pool water heating with PV/T), the water flows through the PV/T collector to heat up the pool water. Mode 4 (PV/T-HP for cooling) operation is analogous to Mode 1 except that the heat pump runs for cooling and provides cold water to the cooling coil of the air handler. This mode operates only at night. In Mode 5 (Pool-HP for cooling), the system operates similarly as Mode 2 except that the heat pump runs for cooling and provides cold water to the cooling coil of the air handler. Mode 6 (pool water cooling with PV/T) operates similarly to Mode 3 except for the pool water is cooled by the water that goes through the PV/T collector at night. Modes 3 and 6 are seasonally active: Mode 3 operates in the winter and shoulder seasons (Oct. 1 to May 31) and Mode 6 operates only in the summer season (Jun. 1 to Sep. 30). In contrast, all other four modes may operate throughout the entire year according to the space thermostat signals. More details about the modes of operation can be found in the authors' previous work (Zare and Wang 2018).

Tab. 1: Operational mode description and control strategy

Operating mode	description	Thermostat signal	Mode activation condition	Yearly time of operation	Daily time of operation
Mode 1	PV/T-HP for heating	Heating on Cooling off	$T_{collector} > 5.6°C$	All year	6 am to 10 pm
Mode 2	Pool-HP for heating	Heating on Cooling off	$T_{collector} < 5.6°C$ $T_{pool} > 1.7°C$	All year	All day
Mode 3	Pool water heating with PV/T	Heating off Cooling off	$T_{collector} > T_{pool}$	Oct. 1 to May 31	6 am to 10 pm
Mode 4	PV/T-HP for cooling	Heating off Cooling on	$T_{collector} < 32.2°C$	All year	10 pm to 6 am
Mode 5	Pool-HP for cooling	Heating off Cooling on	$T_{collector} > 32.2°C$ at night and no conditions during the day	All year	All day
Mode 6	pool water cooling with PV/T	Heating off Cooling off	$T_{collector} < T_{pool}$	Jun 1 to Sep. 30	10 pm to 6 am

In order to avoid mode oscillations, temperature deadbands are introduced to each mode. In this work, the upper and lower deadbands, which are adapted from the 2017 Innovative Energy Project, are set to 5°C and 2°C respectively. Let's use Mode 1 as an example to explain the application of deadbands. Table 1 shows that Mode 1 is activated when the thermostat calls for heating and the PV/T collector temperature is higher than 5.6°C prior to the use of deadbands. After the introduction of deadbands, conditions for activating Mode 1 becomes the thermostat calls for heating and the PV/T collector temperature is higher than 10.6°C (i.e., 5.6°C plus the upper deadband of 5°C). Once initiated, Mode 1 continues as long as the thermostat heating signal is on and the PV/T collector temperature is above 7.6°C (i.e, 5.6°C plus the lower deadband of 2°C). Once the collector temperature falls below 7.6°C, Mode 1 turns off and the PV/T collector temperature needs to reach 10.6°C to reactivate Mode 1. Similarly, temperature deadbands are used in all other modes whenever there is a temperature comparison.

3. House description

The energy performance of the PV/T-HP system was investigated for a hypothetical single-family house in Baltimore, MD. The house has one floor with a total area of 200 m^2, a rectangular shape with an aspect ratio of 0.86, a flat roof with a floor-to-ceiling height of 2.44 m. Slab-on-grade floor and wood-frame constructions are assumed. The window area on each façade is 2 m^2. The house has a 100-m^3 swimming pool. Located on the roof, PVT collector is south-oriented and has a slope of 45° and an area of 39 m^2. Table 2 lists the thermal performance of exterior building envelope that satisfies the residential code requirement (IECC 2006).

Tab. 2: Thermal performance of exterior building envelope

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

4. TRNSYS simulation

The PVT-HP system, the reference system, and the house were modeled and simulated using TRNSYS software. TRNSYS has available library of validated built-in components for renewable energy systems in buildings and can report and integrate parameters like power, mass flow, and temperature over the desired time frame.

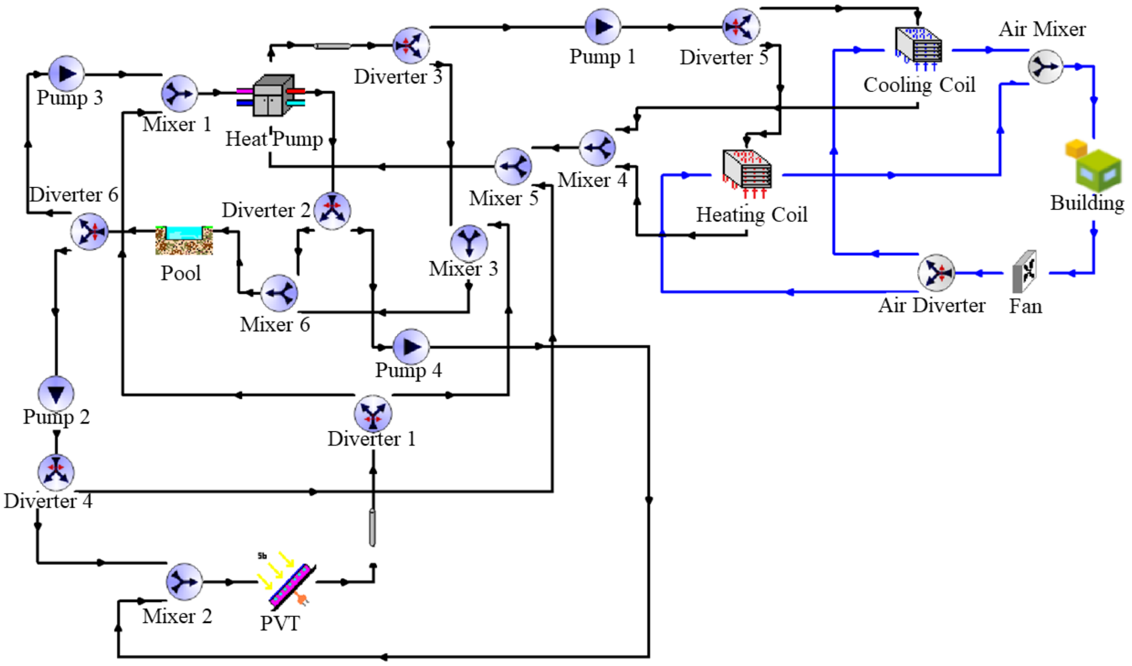

Fig. 2: TRNSYS model

Figure 2 shows the model developed for the proposed PV/T-HP system in TRNSYS. In this figure, water loops are drawn in black while air loops are drawn in blue. Each mode requires different path for the water and air loops. The path of water and air flows are defined by the diverters' control signal and each loops operation is controlled by the pumps' and fan's power control signal. It should be noted that a new TRNSYS type was developed for controlling the system operation. This type recognizes the operating mode based on the space air temperature, the PV/T collector temperature, and the swimming pool water temperature and then provides the control signal to all of diverters, pumps, fan, and heat pump based on the mode of operation.

The building model was first developed in Google Sketchup and subsequently imported into TRNSYS package tool, TRNBUILD, by using TRNSYS3d plugin. The house was modeled using Type 56 multi zone building. Type 166 thermostat was used to monitor the space air temperature with the heating set point of 21°C and a cooling set point of 26°C, each of which has a deadband of 2°C. An air change rate 10 at 50 Pa was assumed for the air infiltration. Internal heat gain was not modeled in this simulation study. Convective heat transfer coefficients of building envelope were calculated dynamically. Space heating and cooling loads were determined by pre-running the annual simulation of the house while keeping the space air temperature in the desired range. The peak heating and cooling loads were found to be 8700 W and 2500 W respectively, which were then used to size TRNSYS components including water-to-water heat pump, water coils and air-source heat pump. Table 3 summarizes the major components, their corresponding TRNSYS Types, and their key parameter settings in the simulation. A 3-ton (10,500 W) commercial water-to-water heat pump product from Water Furnace was referred for the rated and part load water-to-water heat pump efficiency. The supply fan, used in both reference and proposed models, was selected to meet 0.5 w/cfm requirement per IECC (2006). The air flowrate was calculated to meet 11°C temperature difference across the coils. Air-source heat pump's cooling and heating efficiency were set to 14 SEER and 8.2 HSPF respectively based on the residential code requirements in 2013 (Amrane et al. 2010). The SEER and HSPF were converted to the simulation inputs using the approach by Wassmer and Brandemuehl (2006).

Tab. 3: TRNSYS components and their main parameters

Component	TRNSYS type	Main Parameters
PVT Collector (parameters from Xia (2017))	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 Cover removed from May 1 to September 30
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 total efficiency = 0.38 static pressure = 400 Pa
Heating Coil	140	Rated Total Heating Capacity = 10027 W
Cooling Coil	123	Rated Total Cooling Capacity = 5264 W Rated sensible heat ratio = 0.75
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)

5. Results and discussion

TRNSYS simulations of the baseline and proposed systems were performed using the one-minute time step and the typical meteorological year weather data of Baltimore, MD. In the first subsection, the proposed system operation (mode changes based on the main parameter temperatures) is verified for three representative days in winter, summer and shoulder. For each representative day, ambient temperature, the space air temperature, the PV/T collector temperature, the swimming pool water temperature and the resulting active mode are presented to verify the system operation. In the second subsection, the energy performance of the proposed system is presented in terms of its monthly and annual energy savings in comparison with the baseline air-source heat pump system.

5.1. Representative day analysis

January 19, June 25, and October 10 are selected as the representative days of winter, summer, and shoulder respectively. Figures 3-5 show the system operation in the three selected days. Each of these figures show 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}) and the resulting active operational mode.

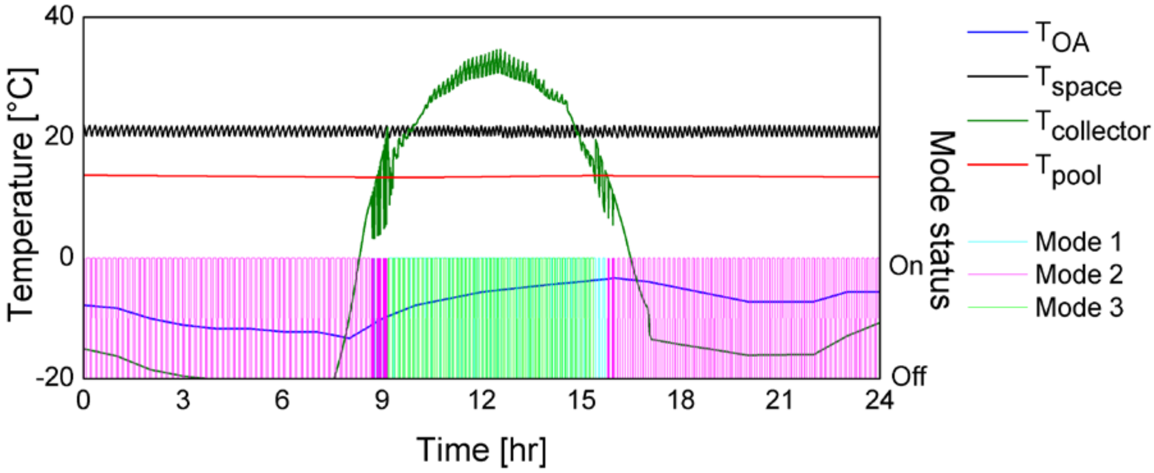

Fig. 3: Operational modes and related temperatures for the system operation on January 19

For the system operation on a winter representative day, Figure 3 leads to the following observations:

- January 19 is a cold winter day for Baltimore with the lowest outdoor air temperature at -14°C. All three possible heating modes (Modes 1, 2, 3) are observed during this day. The thermostat has its heating setpoint at 21°C with a deadband of 2°C (space heating starts when T_{space} reduces to 20°C and it stops when T_{space} reaches 22°C). Mode 2 (i.e., pool-HP for heating, see Section 2) is the active operating mode from 12 am to 9 am, when the thermostat calls for space heating and the PV/T collector and pool temperatures lie in the predefined range (i.e., $T_{collector} < 10.6$°C and $T_{pool} > 6.7$°C). During this time period, Mode 2 cycles on and off, following the same cycle of thermostat heating calls. After 9 am, Mode 1 (PV/T-HP for heating) becomes the active mode when the thermostat calls for space heating because the PV/T collector temperature has increased above 10.6°C. During the period between 9 am and 4 pm, Mode 1 and Mode 3 cycle alternatively: whenever the thermostat calls for heating, Mode 1 is activated; otherwise, whenever the thermostat does not call for heating, Mode 3 (pool water heating) is activated to use PV/T for charging the pool water. The cycle of Modes 1 and 3 continues until around 4 pm when the PVT temperature is lower than 7.6°C. From 4:00 pm to the midnight, Mode 2 cycles on and off with the same behavior and underlying reasons as discussed earlier for the period between 12 am and 9 am.
- Because the outdoor swimming pool is covered and there is a large thermal mass of the pool water, the pool water temperature changes little across the whole day. Starting from 13.8°C at the beginning of the day, the pool water temperature reduces to 13.4°C at 9 am because Mode 2 is activated and the pool water is used as the heat source to provide space heating. From 9 am to 4 pm, the pool water temperature increases to 13.7°C because Mode 3 is activated to charge the pool by PV/T collectors. From 4 pm to the midnight, the pool temperature reduces to 13.5°C because of Mode 2 operation during this period.
- The outdoor air temperature ranges between -14°C and -3°C while the pool water temperature is around 13°C. Such a big difference between the outdoor air temperature and the pool water temperature is the fundamental reason that leads to the higher efficiency of the system than the baseline air-source heat pump system.

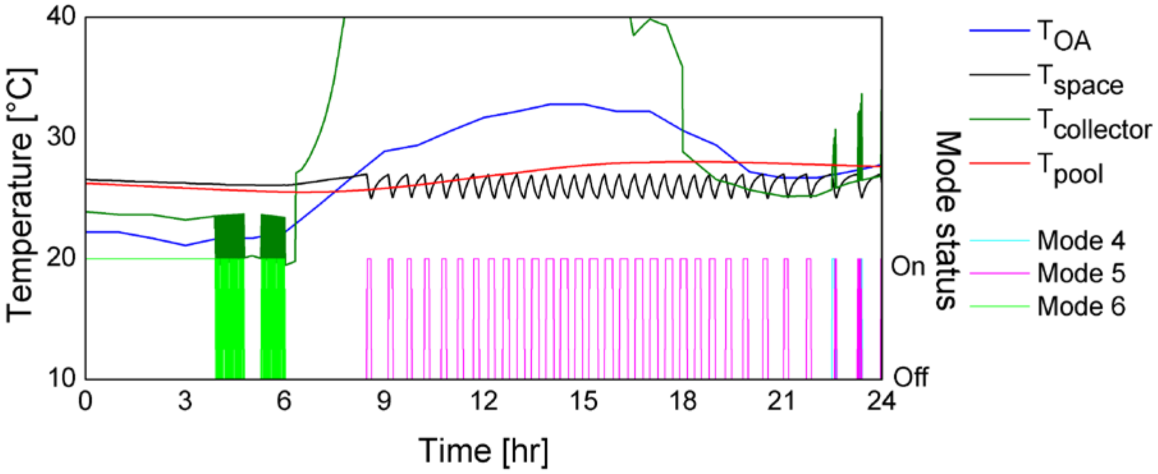

Fig. 4: Operational modes and related temperatures for the system operation on June 25

Figure 4 shows the system operation on June 25, a summer representative day. This figure leads to the following observations:

- June 25 is a hot summer day for Baltimore with peak outdoor air temperature at 35°C. All three possible cooling modes (Modes 4, 5, 6) are observed during this day. The thermostat cooling setpoint is 26°C with the deadband of 2°C. Night time is defined from 10 pm to 6 am and the rest of the day is considered as day time. Mode 6 (i.e., night time pool water cooling, see Section 2) is the active operating mode for the time period of 12 am to 6 am because the PV/T collector temperature is less than pool temperature. Through this mode, night time radiative cooling is used to reduce the pool water temperature. The thermostat first calls for space cooling at 8:30 am and Mode 5 (pool-HP for cooling) becomes the active mode. From 8:30 am to midnight, Mode 5 cycles on and off, following the same cycle of thermostat cooling calls. Mode 5 operation time in each cycle increases until 2 pm, which is the hottest time of the day, and decreases afterwards. The only exception to this cycle happens at 10:30 pm when thermostat calls for space cooling while PV/T collector temperature is less than 27.2°C and therefore Mode 4 (night time PV/T-HP for cooling) is the active operating mode.

- The pool cover is removed from May to September and therefore pool is uncovered in this summer representative day and consequently more pool temperature change compared to the wintertime is noticeable. Starting from 26.3°C at the beginning of the day, the pool water temperature reduces to 25.5°C at 7 am because of two reasons: 1) Mode 6 activation and radiative cooling of the pool; 2) heat transfer to the cooler outdoor air. From 7 am to 6 pm, the pool water temperature increases to 28°C because: 1) Mode 5 is activated and the pool water is used as the heat sink to provide space cooling; 2) heat transfer with warmer outdoor air happens. From 6 pm to 12 am, the pool water temperature is reduced to 27.6°C since the pool's heat loss because of heat transfer with cooler surrounding area overcomes the pool's heat gain from Mode 5 operation.

- The outdoor air temperature ranges between 20°C and 35°C while the pool water temperature range is between 25°C and 28°C. The pool water temperature is mostly lower than the outdoor air temperature when space cooling is needed, which leads to the higher cooling efficiency of the proposed system compared to the baseline air-source heat pump system.

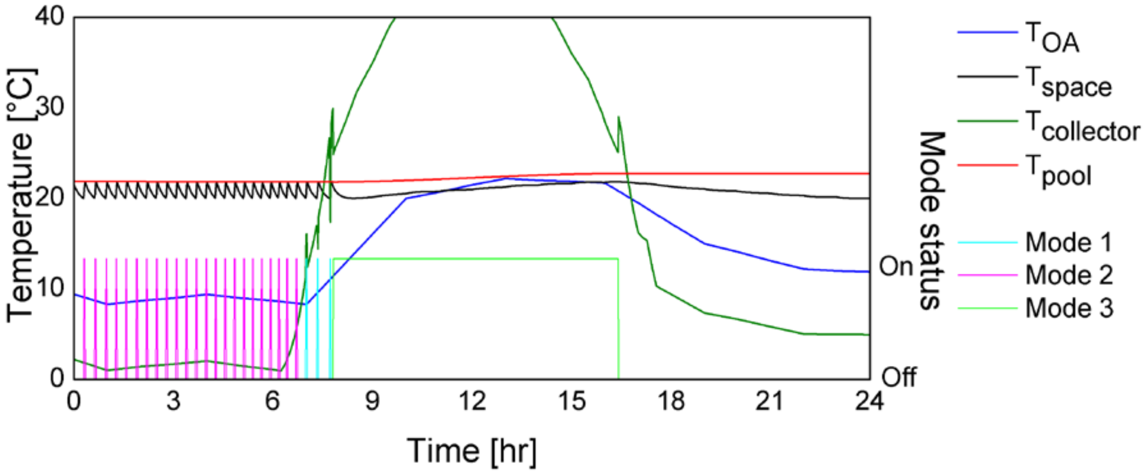

Fig. 5: Operational modes and related temperatures for the system operation on October 10

Figure 5 shows the system operation on October 10, a shoulder representative day. This figure leads to the following observations:

- The outdoor air temperature is around 8°C during early hours of the day and there are several occasions when the thermostat calls for heating during this day. Before 7 am, the temperature of the PV/T collector is low. Thus, Mode 2 (pool water space heating) is activated whenever the thermostat calls for space heating. Between 7 am and 8 am, Mode 1 (PV/T-HP for heating) is activated three times, each of which lasts about one minute. Between 8 am and 4:30 pm, Mode 3 (pool water heating through PV/T collector) runs consistently because no space heating is needed and the PV/T collector temperature is higher than the pool water temperature.
- Starting from 21.8°C, the pool water temperature has negligible changes in the early hours of the day because of the large thermal mass of the pool. However, the continuous operation of Mode 3 for more than 8 hours increases the pool water temperature by 1°C.

5.1. Energy consumption comparison

After verifying the system operation through representative days, the simulation was ran for a whole year to compare the energy consumption between the proposed PV/T-HP system and the baseline split air-source heat pump system. Figure 6 shows the energy consumption of each month and the whole year for both systems. The energy consumption reported here comes from the water-to-water heat pump, pumps, and the supply fan for the proposed system while it is from the air-source heat pump and the supply fan for the baseline system. Figure 6 indicates the following:

- The proposed system is much more efficient than the reference system during the heating season. Specifically, the proposed system consumes 67%, 64%, 58%, 71%, 85%, and 90% of the reference system energy consumption, sequentially from November to April. As mentioned earlier, the heating efficiency mainly comes from the elevated source side temperature (pool water temperature or PV/T collector temperature for the proposed system vs. outdoor-air temperature for the baseline).
- In the cooling season, the proposed system consumes 95%, 87%, 84%, and 108% of energy consumption by the baseline system respectively in June, July, August, and September. These percentages of energy savings are less than those in winter months. The major reason is that the benefits of energy saving from using pool water for cooling at daytime are significantly offset by the pump energy incurred at nigh time when Mode 6 operation (pool water cooling with PV/T) runs almost continuously. In particular, in September, the magnitude of cooling energy consumption is much lower than other months, which makes the pump energy more significant and thereby leads to more energy consumption than the baseline system.

- In May and October of the shoulder season, the proposed system consumes 83% and 73% of energy consumption by the baseline system. Let's use October as a good example of how the pool heating can make the proposed system more efficient. As the representative day analysis in Figure 5 shows, Mode 3 (pool water heating with PV/T) is the dominant mode during day time because of the high PV/T collector temperature and negligible heating needs. This means that more thermal energy is charged to the pool water than the discharged thermal energy and parasitic heat losses. As a result, favorable pool water temperature exists for the source side of the water-to-water heat pump when heating is needed during this month and even the following months (November and December). This can explain to some extent why the three months (October to December) have the highest percentage of energy savings.
- For the whole year, the proposed PV/T-HP system consumes 70% of annual energy consumption by the baseline system. This value is close to the average percentage of energy savings in the heating season because heating energy dominates the overall HVAC energy use by the modeled house in Baltimore.

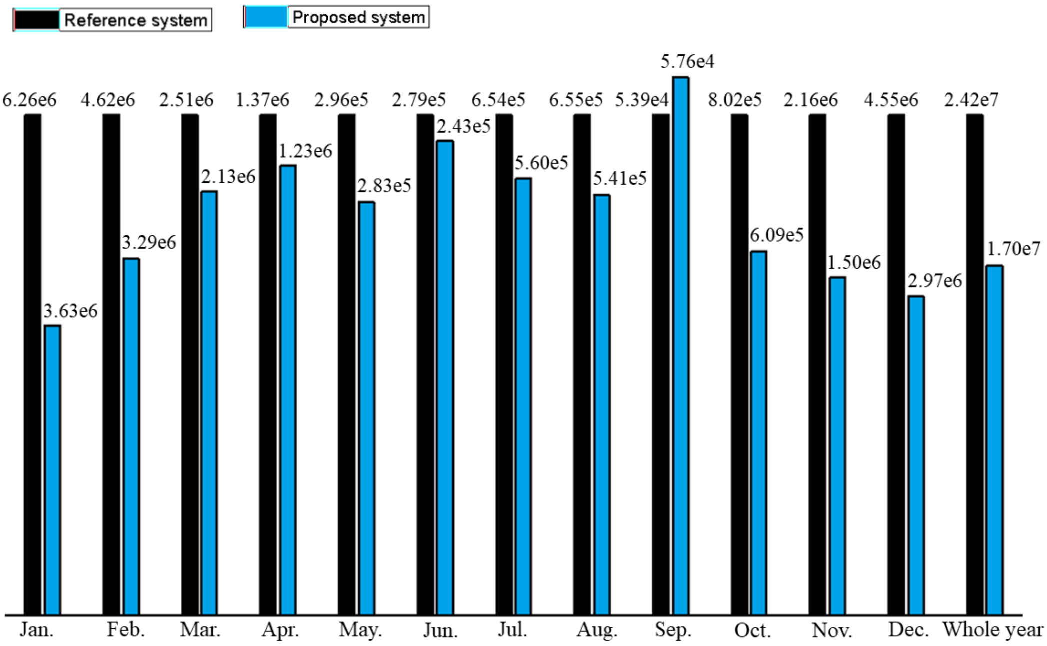

Fig. 6: Onsite energy consumption comparison between the baseline and proposed systems. The energy consumptions are reported in KJ.

6. Conclusions

This paper presents the simulated performance of a proposed hybrid PV/T heat pump system in a 200-m^2 one-floor house in Baltimore, MD. The proposed system includes a water-to-water heat pump, a PV/T collector, an outdoor swimming pool, pumps, and a forced air system containing water coils and a fan for air conditioning. The proposed system uses a six-mode control strategy that decides the active operating mode based on the space air temperature, the PV/T collector temperature, and the swimming pool water temperature. In the proposed system, the PV/T collectors are used to collect thermal energy and either deliver it to the water-to-water heat pump for space conditioning or store it in the outdoor swimming pool. On the other hand, the charged pool is the source/sink for the water-to-water heat pump when the PV/T collector is not capable of providing enough thermal energy. TRNSYS software was used to study the performance evaluation of the proposed system. The system operation was verified through three representative days in the winter, summer and shoulder months and the system operated as expected in all three representative days. After system operation verification, energy consumption of the proposed system was compared to a split air-source heat pump system. Based on the annual and monthly simulation results, the average monthly energy consumption of the proposed system in the winter, summer, and shoulder months were 72%, 93%, and 78%

of the baseline energy consumption respectively, and the annual energy saving of the proposed system compared to the baseline system was 30%. The experimental or field test verification of the proposed system, addition of the domestic hot water production, and exploring strategies for generated PV electricity self-consumption in the system are the suggested directions for the future of this research.

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