Performance Simulation of a Ground Source Heat Pump System Integrated with Solar Photovoltaic Thermal Collectors for Residential Applications

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Abstract

This paper presents the simulation and performance evaluation of a ground source heat pump (GSHP) system integrated with water-based solar photovoltaic thermal (PVT) collectors for residential buildings. The proposed system utilizes geothermal energy and solar energy to provide space cooling and heating as well as domestic hot water (DHW), and offsets the need of grid electricity by generating electricity from the PV cells. A dynamic simulation system is developed using TRNSYS and used to facilitate the performance evaluation of the proposed system. A 20-year life-time performance simulation is performed under three operation scenarios with different sizes of the PVT collectors. The results showed that the performance of the proposed system is highly dependent on the size of the PVT collectors. For the case building studied, it is more effective to use the heat gathered by the PVT collectors to produce DHW if the area of the PVT collectors is less than 54 m^2. Otherwise, it is better to use the thermal energy generated from the PVT collectors to recharge the ground during the transient periods and to provide space heating during the heating period. Furthermore, an economic analysis is carried out to determine the optimum size of the PVT collectors for the case study building. The results from this study demonstrate how building simulation offers the capability in analyzing and determining the optimal operation strategies for complex energy systems at the design stage.

Introduction

Space heating and domestic hot water (DHW) account for a large amount of energy consumption in residential buildings, especially in cold climates (Eicher et al., 2014; Fischer et al., 2016). With the global resource depletion and climate change, exploring substitutes of traditional heating and DHW systems to reduce energy consumption and carbon dioxide emissions becomes increasingly important. Some alternative energy sources such as geothermal energy and solar energy have a great potential for the development of low energy buildings.

A hybrid ground source heat pump (GSHP) systm integrated with water-based photovoltaic thermal (PVT) collectors could provide cooling, heating as well as DHW, and offset the need of grid electricity using the electricity generated from the PV cells.

Significant research has been carried out on the coupling of GSHP systems with solar thermal collectors. For example, Trillat-Berdal et al. (2007) described a GSHP system coupled with solar thermal collectors for building heating, cooling and DHW production for a 180 m^2 residential building. The energy performance of the system was analyzed using TRNSYS simulation. Kjellsson et al. (2010) analyzed different systems by combining solar thermal collectors with a GSHP system. The results showed that the optimal design was achieved when solar heating was used to produce domestic hot water during summertime and recharge the boreholes during wintertime. Mehrpooya et al. (2015) investigated the optimum performance of a combined solar thermal collector and GSHP system to meet the heating load of greenhouses. The results indicated that the selected system has a mean seasonal coefficient of performance of 4.14, with the borehole length of 50 m, the borehole number of 3 and the total solar collector area of 9.42 m^2.

However, the research for the hybrid GSHP-PVT systems has not been extensively conducted. Bakker et al. (2005) simulated the performance of a GSHP-PVT system in a family dwelling with a floor area of 132 m^2 in Netherlands. The results showed that the PVT collector with an area of 54 m^2 can cover 100% of the total heating demand of the dwelling and nearly all electricity demand while keeping the long-term average ground temperature constant. Entchev et al. (2014) compared the performance of a GSHP-PVT system with a conventional boiler and chiller system and a stand-alone GSHP system under Ottawa, Canada, weather conditions. The simulation results showed that the stand-alone GSHP system and the hybrid GSHP-PVT system can result in an overall energy saving of 46% and 58% respectively, as compared to the conventional system. Canelli et al. (2015) analyzed the performance of a hybrid GSHP system with fuel cells and a GSHP-PVT system in Napoli, South Italy. Compared to a conventional system with boilers and chillers, the primary energy savings of the GSHP system with fuel cells and the GSHP-PVT system were 12.8% and 53.1%, respectively. Putrayudha et al. (2015) presented a study where the energy consumption of a GSHP-PVT system was optimized by using a fuzzy logic control. The results showed that the system with the fuzzy logic control consumed 18.3% less annual energy in comparison with the same system with on-off control. Brischoux and Bernier (2016) examined the performance of a coupled GSHP-PVT system for space heating and DHW heating. The results showed that the coupled GSHP-PVT system can provide 7.7% more electricity annually with a higher seasonal performance factor in comparison with an uncoupled system.

The existing studies of GSHP-PVT systems were mainly focusing on the performance evaluation and performance comparison among different heating and cooling systems under a given PVT collector area. The results from these studies were, however, highly dependent on the size of the PVT collectors used. To date, to the best of our knowledge, there is no relative research that has studied the influence of the PVT size on the performance of the GSHP-PVT system in details and discussed the effect of the PVT size on the operation of hybrid GSHP-PVT systems.

In this study, a GSHP system integrated with water-based PVT collectors is proposed to provide cooling, heating and DHW for residential buildings. Three different operation scenarios of the system are designed and the simulation systems for each scenario are developed. The effect of the PVT size on the performance of the three operation scenarios is investigated in a case study building under the weather condition of Melbourne, Australia. An economic analysis is also carried out to determine the optimum PVT size for the case study building.

System development and operation scenarios

The proposed GSHP-PVT system is schematically illustrated in Figure 1. The system is mainly designed to provide heating and cooling, as well as DHW for heating dominated buildings. The system consists of PVT collectors, water tanks with immersed heat exchangers, a water-to-water heat pump unit, water circulation pumps, a ground heat exchanger loop and an indoor air-handling unit (AHU). This system can operate under different modes, as described in Table 1, to provide functional requirements of the house.

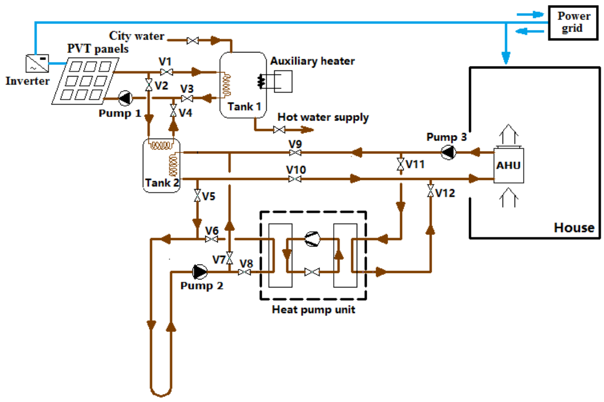


Figure 1: Schematic diagram of the proposed GSHP-PVT system.

Table 1: Operation modes of the GSHP-PVT system

Mode	Description
PVT for space heating	Using the heat generated from the PVT collectors for space heating.
GSHP for space heating/cooling	Using GSHP for space heating and cooling.
PVT for ground recharging	Using the thermal energy collected from the PVT to recharge the ground.
PVT for DHW heating	Using the thermal energy from the PVT collectors for DHW.

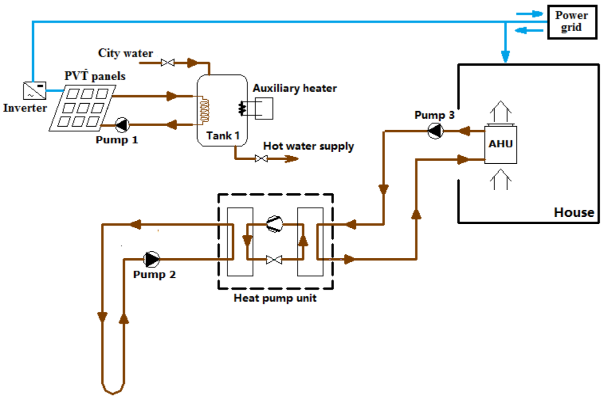
Three operation scenarios for this proposed GSHP-PVT system are considered in order to evaluate and determine the optimal approach to using the thermal energy generated from the PVT collectors at the design stage. The schematics of each scenario are shown in Figure 2 and the detailed operation of the system in each scenario are summarized in Table 2.

In scenario 1 (Figure 2a), the GSHP system is designed to satisfy the cooling and heating demands of the house while the PVT collectors are used to produce DHW and electricity for the house. Ground recharge is not considered in this scenario.

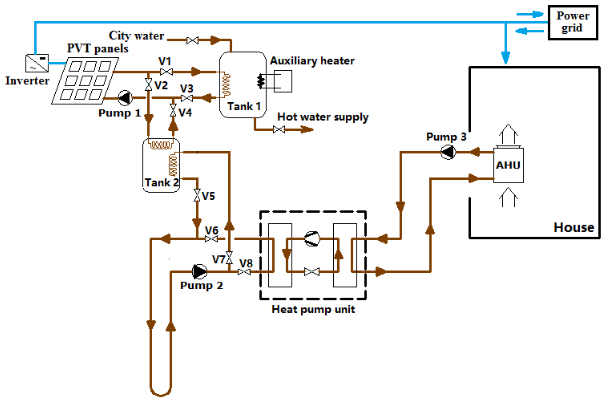
In scenario 2 (Figure 2b), the thermal energy collected from the PVT collectors is used to generate DHW in the cooling and heating periods. During the transition periods, the thermal energy generated from the PVT collectors is first used to heat the water in tank 2 for ground recharging in order to achieve annual thermal balance of the ground, and is then used to heat the water in tank 1 to produce DHW if the ground recharge has been completed. The ground recharge is implemented if the water temperature in tank 2 is above a temperature setting predetermined. The GSHP system is used to provide the cooling and heating demands of the house, similar to that in scenario 1.

In scenario 3 (Figure 2c), the thermal energy generated from the PVT collectors is used in the same way as that in scenario 2 during the cooling and transition periods. In the heating period, the heat generated from the PVT collectors is used for space heating when the water temperature in tank 2 reaches the temperature set-point predetermined. The GSHP system is used to provide space heating when the water temperature in tank 2 is lower than the temperature set-point.

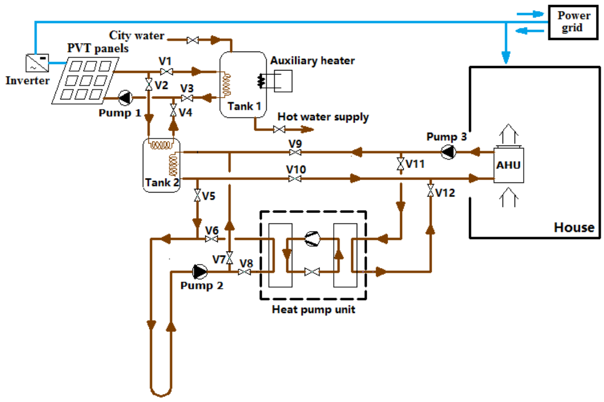
In the above three scenarios, the auxiliary heater is used when the thermal energy generated by PVT collectors is not able to keep the water temperature in tank 1 above 60°C. 60°C is the minimum temperature requirement for hot water storage specified in the Australian and New Zealand National Plumbing and Drainage guidelines (Standard Australia, 2003).



(a) Scenario 1



(b) Scenario 2



(c) Scenario 3

Figure 2: Schematic of three operation scenarios.

Table 2: Summary of the operation scenarios

Scenario	Heating	Cooling	Ground recharge	DHW production
1	GSHP	GSHP	No	PVT + auxiliary heater
2	GSHP	GSHP	Yes	PVT + auxiliary heater
3	PVT + GSHP	GSHP	Yes	PVT + auxiliary heater

System modelling

In this study, the three operation scenarios of the hybrid GSHP-PVT system are simulated using TRNSYS (2016). The component models used are the standard models provided in the TRNSYS library and are summarised in Table 3. The simulation system developed for scenario 2 is shown in Figure 3, as an example.

Table 3: Simulation models used in this study

Component	TRNSYS type	Description
Water-to-water heat pump	Type 927	Performance data-based single-stage water-to-water heat pump
Ground heat exchanger	Type 557a	Vertical U-tube GHE
PVT collector	Type 563	Unglazed photovoltaic thermal collector
Hot water tank	Type 534	Constant volume storage tank with an immersed heat exchanger
Auxiliary water heater	Type 1226	Auxiliary heater
Circulation pump	Type 110	Variable speed pump

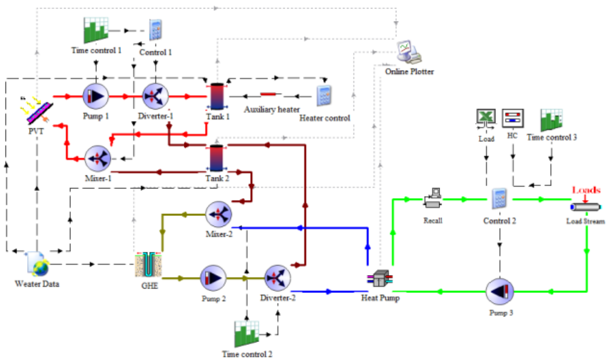


Figure 3: Illustration of the simulation system developed in TRNSYS for scenario 2.

The water-to-water heat pump model was trained using the manufacturing catalogue data. The key parameters of the PVT, GHEs, water tank and water pumps were determined using the available product specifications, which will be introduced in the following section.

Case study

Building model and load characteristics

A two-story Australian house (Craig and Savanth, 2016) with a floor area of 248 m^2 and the conditioned area of 200 m^2 is used for the performance analysis. The house model was developed in DesignBuilder, and is shown in Figure 4.

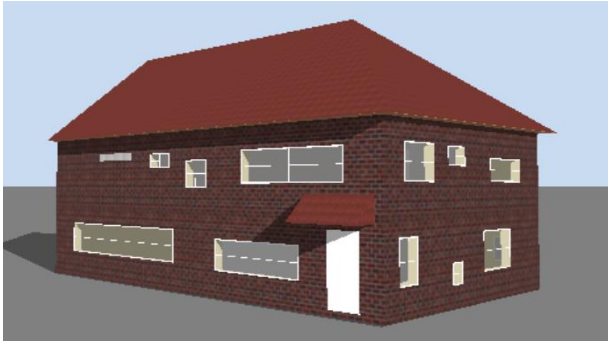


Figure 4: The house model developed in DesignBuilder.

The heating and cooling thermostat settings used in the load calculation were specified according to Nationwide House Energy Rating Scheme (NatHERS, 2012). For the living spaces, the heating thermostat setting was set to 20ºC. For sleeping spaces, a heating thermostat setting of 18ºC from 7:00 to 9:00 and 16:00 to 24:00, and 15ºC from 9:00 to 16:00 and 24:00 to 7:00 was used. The cooling thermostat was set as 24.0ºC.

The annual heating and cooling demands of the house were simulated using DesignBuilder based on the weather data from International Weather for Energy Calculations (IWEC) of Melbourne and are presented in Figure 5. Table 4 summarizes the design load and the annual load requirement of the house, which were determined based on the maximum values presented in Figure 5.

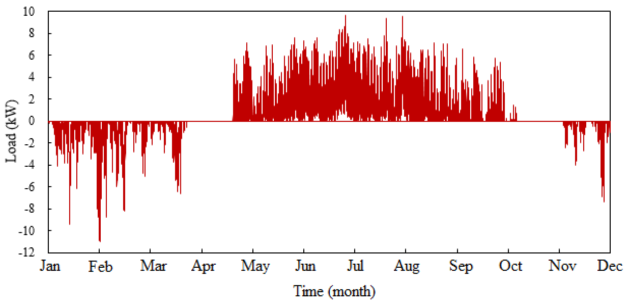


Figure 5: Heating and cooling load profile of the house.

Table 4: House load requirements

Mode	Design Load (kW)	Annual accumulated load requirement (kWh)	Total number of hours
Cooling	13.2	2,030	1,431
Heating	11.6	6,567	3,281

According to the load simulation results, the annual load profile was categorized into five time periods as illustrated in Figure: 6. This categorization was mainly designed for ground recharge purposes by assuming that there is no heating and cooling demand of the house during the transition periods. The heating period started from 1st May to 31st October. The cooling period was from 1st December to 31st March. The remaining periods were considered as the transition periods.

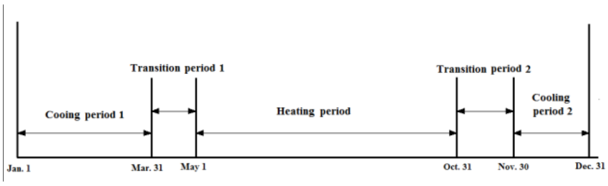


Figure 6: Heating, cooling and transition periods defined.

Component sizing

The proposed GSHP-PVT system can be divided into two sub-systems: GSHP sub-system and PVT sub-system. The GSHP sub-system includes the heat pump unit and GHE system which were designed to satisfy the heating and cooling demands of the house. The parameters of the GSHP system were determined based on the design load listed in Table 4 and the product specification available from the manufacturer (WaterFurnace, 2016).

The specifications of the GHE system were derived based on the studies of Lhendup et al. (2014a; 2014b), and are summarized in Table 5. It is worthwhile to note that the values presented in Table 5 are not necessarily the optimal values for the GSHP system.

Table 5: Specifications of the GSHP system

Parameter	Value
GHE system (Lhendup et al., 2014a; 2014b)	
Borehole depth (m)	40
Number of boreholes	6
Borehole distance (m)	8
Ground thermal conductivity (W/(m.K))	2.23
Ground heat capacity (KJ/(m^{3}K))	2300
Borehole diameter (m)	0.115
Outer diameter of U-tube (m)	0.025
Initial ground temperature (ºC)	15.9
Heat pump unit (WaterFurnace, 2016)	
Rated cooling/heating capacity (kW)	11.5/13.6
Water flow rate (m^3/h)	2.3
Rated power consumption (kW)	2.80/3.17

The PVT sub-system consists of the PVT collectors, tank 1 with an auxiliary heater and tank 2. The parameters of the PVT collectors used in the simulation were determined by referring to the study from Fudholi et al. (2014) and are summarized in Table 6. The top loss convection coefficient for the unglazed PVT collector was calculated by referring to the study of Anderson et al. (2009), in which both nature and forced convection were considered. The forced wind heat transfer coefficient h_w was calculated using Watmuff et al. (1977) correlation in terms of wind velocity v:

$$h_w=2.8+3.0v. \tag{1}$$

The natural convection loss h_n was calculated as a function of the temperature difference between the mean collector temperature T_{pm} and the ambient temperature T_a (Eicker, 2003):

$$h_n=1.78(T_{pm}-T_a)^{1/3}. \quad (2)$$

Ten different sizes of the PVT collectors with 24, 30, 36, 42, 48, 54, 60, 66, 72 and 78 m^2 were considered in this study to examine the impact of the PVT size on the performance of the proposed system. Trial simulations of scenarios 2 were performed and it was found that 24 m^2 was the minimum area of the PVT collectors that can achieve annual ground thermal balance through recharging the ground in the transition periods, while 78 m^2 was determined as the maximum area of the PVT collectors covering the north rooftop area of the house. The parameters of all circulation pumps used in the system are summarized in Table 7.

Table 6: Summary of main design parameters of the PVT system

Parameter	Value
PVT collector (Fudholi et al., 2014)	
Absorptivity	0.9
Emissivity	0.8
Electrical efficiency at standard conditions	12%
Absorber plate thickness (m)	0.002
Absorber thermal conductivity (W/m·K)	51
Back material thickness (m)	0.05
Back material thermal conductivity (W/m·K)	0.045
Insulation conductivity (W/m·K)	0.045
Number of water tubes	100-340
Outer diameter of water tube (m)	0.02
Other relevant parameters	
Volume of tank 1 (Vieira et al., 2014) (L)	250
Volume of tank 2 (L)	250
Power of auxiliary heater (kW)	5.0

Table 7: Design parameters of circulation pumps

Name	Function	Parameters
Pump 1	Circulation of water between PVT and water tanks	Flow rate: 0.2-0.68 kg/s; Power: 45-70 W. Efficiency: 40%-55%
Pump 2	Source side circulation and ground recharge	Rated flow rate: 0.65 kg/s; Rated power: 94 W. Efficiency: 58%
Pump 3	Load side circulation	Rated flow rate: 0.65 kg/s; Rated power: 70 W. Efficiency: 55%

In the simulation, pump 1 is switched on when the instantaneous solar radiation exceeds 300 W/m^2 and the outlet water temperature of PVT is greater than the water temperature in tank 1 or tank 2.

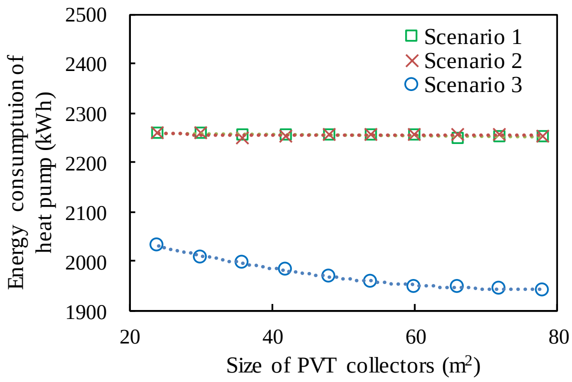
The ground recharge in scenarios 2 and 3 is implemented when the water temperature in tank 2 is over 30°C during the transition periods. When thermal energy transferred to the ground can maintain the annual ground thermal balance, the heat energy generated from the PVT will then be used for DHW.

The PVT for space heating in scenario 3 is switched on when there is a heating demand of the house and the water temperature in tank 2 is over 40°C.

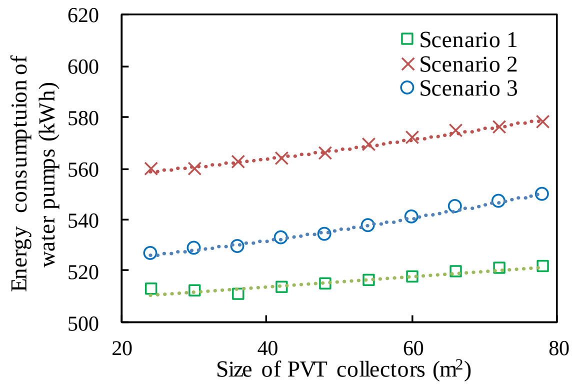
Results and discussion

Annual energy consumption

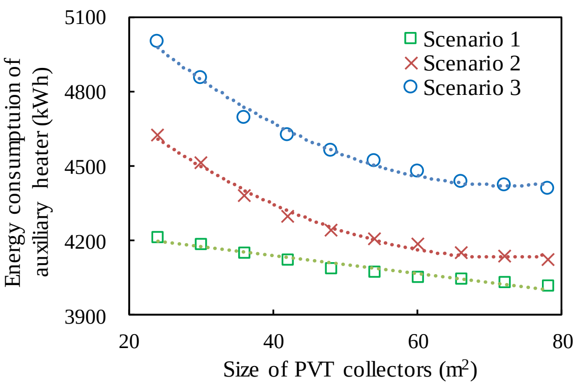
The influence of the PVT size on the annual energy consumption of the system for the three scenarios in the first year operation is first investigated, and the results are presented in Figure 7.



(a) the heat pump unit.



(b) the water pumps



(c) the auxiliary heater

Figure 7: Annual energy consumption of different components with different sizes of the PVT collectors.

It can be seen that the annual energy requirement of the heat pump unit in scenario 1 was nearly the same as that in scenario 2 as the PVT was not used for space heating and cooling purposes. The annual energy use of the heat pump in scenario 3 is lower than that in the other two scenarios and it reduced with the increase of the PVT size because a fraction of the heating demand of the house was provided by the PVT collectors (Figure 7a).

The annual energy consumption of the water pumps slightly increased with the increase of the PVT area but the change was small (Figure 7b). Among the three scenarios, the water pumps in scenario 2 consumed the highest amount of energy while the pumps in scenario 1 consumed the lowest amount of energy (Figure 7b). The annual energy consumption of the auxiliary heater decreased with the increase of the PVT area in all three scenarios since a larger PVT area can provide more thermal energy for DHW (Figure 7c). As the thermal energy collected from the PVT is first used to recharge the ground and then provide heating for the house in scenario 3, a higher energy demand for running the auxiliary heater was therefore needed as compared to that of the other two scenarios. It is worthwhile to note that in the three scenarios, the auxiliary heater was generally used during the night-time once the DHW in tank 1 has been partially or fully consumed.

Figure 8 presents the annual total energy consumption of the system under the three scenarios with different areas of the PVT collectors for the first year of operation. The annual energy consumption of the three scenarios decreased with the increase of the PVT area. In scenario 1, the annual energy consumption almost linearly decreased from 7,050 kWh to 6,837 kWh when the area of the PVT increased from 24 m^2 to 78 m^2. The system consumed more energy under scenario 3 than under scenario 2 when the area of the PVT collectors was less than 48 m^2. This means that, in the heating period, for the system with a smaller PVT size, it is worthwhile to use the thermal energy collected from the PVT to produce DHW, while for the system with a larger PVT size, it is better to use the thermal energy collected from the PVT to provide space heating. The system operated under scenario 1 consumed the least energy for all different PVT sizes considered in the first year operation.

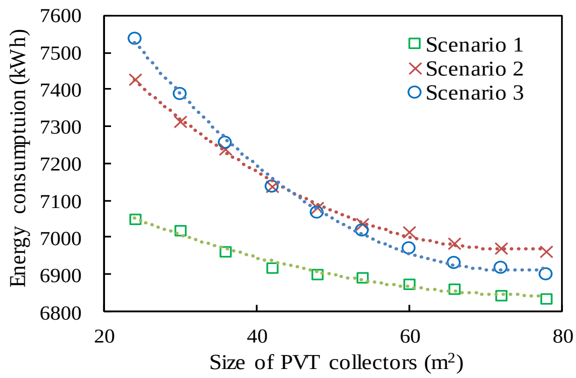


Figure 8: Annual energy consumption of the system under three scenarios with different sizes of PVT collectors.

Variation of the ground temperature

Figure 9 shows the variation of the ground temperature during the first year of operation under the three operation scenarios. It can be seen that the ground temperature was almost equal to its initial value at the end of the first year in scenarios 2 and 3 due to the provision of ground recharging. However, the ground temperature reduced by 0.5ºC after the first year of operation under scenario 1.

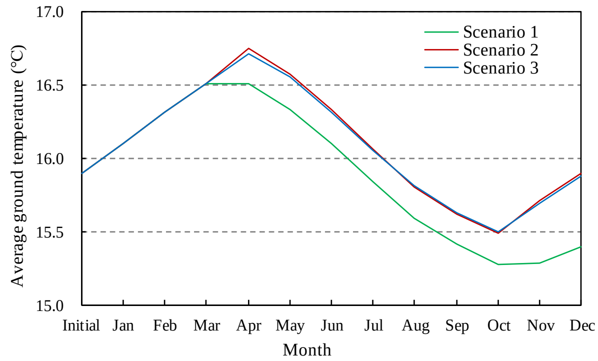


Figure 9: Variation of the ground temperature in the first year operation.

20-year life time performance evaluation

Figure 10 shows the 20-year variations of the ground temperature when the system operated under the three different scenarios. The ground temperature decreased from 15.9ºC to 7.5ºC at the end of the 20th year under scenario 1 with an average annual temperature decrease of 0.4ºC. A good balance of the ground temperature can be achieved when the system operated under scenarios 2 and 3.

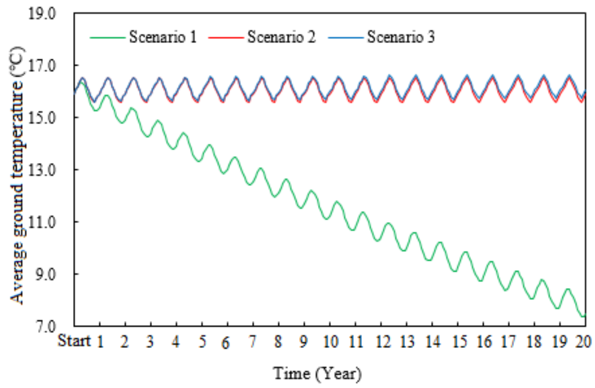


Figure 10: Variation of the ground temperature in 20 years operation.

The decrease of the ground temperature in scenario 1 deteriorated the performance of the heat pump unit, leading to the gradual increase of the annual energy consumption of the system. The annual energy consumption of the system under scenarios 2 and 3 remained constant due to the ground thermal balance. Figure 11 illustrates the variation of the system energy consumption during 20 years operation with the PVT area of 48 m^2, as an example.

The 20-year life time total energy consumption of the system with different sizes of the PVT collectors under the three operation scenarios is presented in Figure 12. The life time total energy consumption of the system decreased with the increase of the PVT area for all three scenarios and a large variation can be observed in scenario 3. It was found that it is better to use scenario 1 when the size of the PVT collectors is less than 54 m^2, while it would be more beneficial in terms of energy use to use scenario 3 when the size of the PVT collectors is greater than 54 m^2 for this case study building.

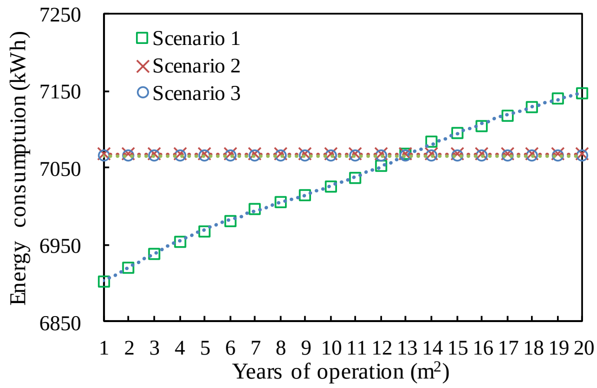


Figure 11: Variation of the annual system energy consumption under three scenarios with the PVT area of 48 m^2 in 20 years operation.

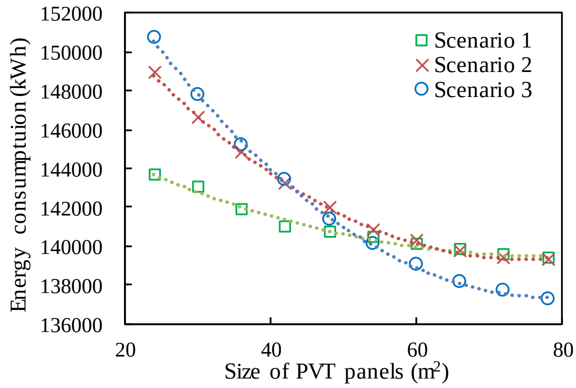


Figure 12: 20-year life time energy consumption of the system with different PVT sizes under three scenarios.

As a limitation of this analysis, it should be mentioned that the climate conditions used for 20-year simulation were assumed to remain the same each year. It should be noted that as the variation of the ground temperature is subjected to the variations of weather condition, soil conditions, and the heat extraction and rejection, the overall simulation results could be different if projected climate conditions are used. The uncertainty associated with the projected ground temperature will also be influenced by the uncertainty of the projected climate conditions.

Selection of the optimum PVT size

The annual electricity generation of the system with different PVT sizes is presented in Figure 13.

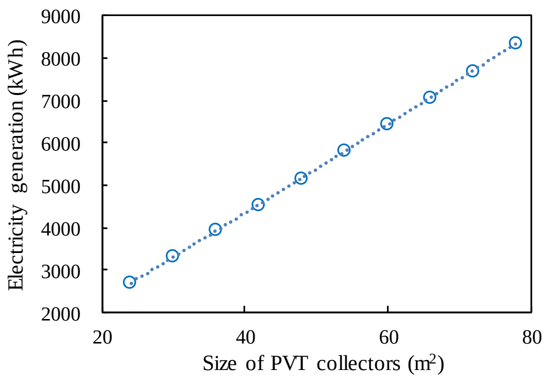


Figure 13: Annual electricity generation of the system with different PVT sizes.

It can be seen that the annual electricity generation almost linearly increased with the increase of the PVT size. When combining Figure 12 and Figure 13, it can be concluded that increasing the PVT size will certainly reduce the electricity consumption of the PVT-GSHP system and it will obviously provide more electricity generation. However, increasing the PVT size would also lead to an increased initial investment for purchasing the system. An economic analysis is therefore needed to determine the optimum PVT size for the proposed GSHP-PVT system. In this study, the net present value (NPV) of life-time total cost of the system was adopted as the objective, which consists of the initial cost and the 20-year operational cost. The NPV value is calculated through Eq. (3) (Alavy et al., 2013):

$$NPV = \sum_{t=0}^{N} \frac{CF_t}{(1+IR)^t} \tag{3}$$

where CF_t is the cash flow at year t, IR is the interest rate, and N is the years of operation.

Table 8 summarizes the input parameters used for calculating the NPV of the system. The costs of GHE and heat pump unit were calculated based on the study of Huang et al. (2014). The price of the PVT collector referred to the study of Matuska and Sourek (2013). The interest rate was chosen according to the value provided by Trading Economics (2016). The average electricity price for residential buildings in Melbourne is 0.26 \$/kWh and any excess electricity generated by the system can be sold back to the grid with the price of 0.05 \$/kWh according to the feed-in tariff scheme in Victoria 2016 (Essential Services Commission, 2016).

The annual energy consumptions and electricity generations of the system with different PVT areas during its life-time were obtained through the simulation. Based on the analysis in the previous section, the annual energy consumption of the system was determined based on the operation scenario 1 when the PVT area is less than 54 m^2. Otherwise, it was determined based on the operation scenario 3 for economic analysis. The NPV value of the total cost of the system with deferent sizes of the PVT collectors were calculated consequently based on the simulation outcomes and the values listed in Table 8. Figure 14 presents the economic analysis results in terms of the 20-year NPV of the system. It can be seen that the system with the PVT area of 66 m^2 has the highest NPV of -$51,795.

Table 8: Input parameters for calculation of NPV

Parameter		Cost
GHE	$	20,400
Heat pump unit	$/each	6000
Water tank	$/each	840
Water circulation pumps	$	140
PVT collector	$/m^2	360
Electricity price	$/kWh	Buy: 0.26 Sell: 0.05
Interest rate	%	1.5

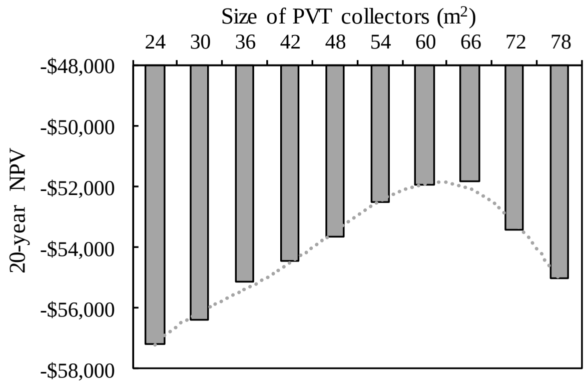


Figure 14: 20-year net present value of the system with different PVT sizes.

The analysis of the simulation results showed that the PVT size has a siginificant influence on both the thermal and electricity outputs of the GSHP-PVT system and consequently affects the performance of the whole system. In general, the system with a larger PVT area consumes less energy and produces more electricity. However, an additional upfront cost will offset the benefit obtained. Therefore, the PVT size should be appropriately sized and the system should be properly contolled to maximize the economic value of hybrid GSHP-PVT systems.

Conclusion

This study presented the simulation and performance evaluation of a ground source heat pump (GSHP) system integrated with water-based solar photovoltaic thermal (PVT) collectors under three different operation scenarios. The simulation exercises based on a case study building showed that the PVT size has a significant influence on the overall performance and operation strategies of the hybrid GSHP-PVT system. For the case building studied, it is more effective to use the heat generated by the PVT collectors to produce domestic hot water (DHW) if the area of the PVT collectors is less than 54 m^2. Otherwise, it is better to use the heat generated by the PVT collectors to recharge the ground during the transition periods and to provide space heating in the heating period. The result from the 20-year life-time economic analysis of the system showed that the optimum PVT size for the case building is 66 m^2, since the system with the PVT size of 66 m^2 has the highest net present value (NPV) of -$51,795. This study demonstrates how building simulation tools offer the capability of analyzing and selecting control strategies for complex low energy systems at design stage.

References

Alavy, M., Nguyen, H. V., Leong, W. H. & Dworkin, S. B. (2013). A methodology and computerized approach for optimizing hybrid ground source heat pump system design. *Renewable Energy 57*, 404-412.

Anderson, T. N., Duke, M., Morrison, G. L., & Carson, J. K. (2009). Performance of a building integrated photovoltaic/thermal (BIPVT) solar collector. *Solar Energy 83*(4), 445-455.

Bakker, M., Zondag, H., Elswijk, M., Strootman, K. & Jong, 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.

Brischoux, P., and Bernier, M. (2016). Coupling PV/T collectors with a ground-source heat pump system in a double U-tube borehole. *ASHRAE winter conference, Orlando, Florida, January 2016*. Paper OR-16-C046.

Canelli, M., Entchev, E., Sasso, M., Yang, L. & Ghorab, M. (2015). Dynamic simulations of hybrid energy systems in load sharing application. *Applied Thermal Engineering 78*, 315-325.

Craig, J and Savanth, S. (2016). *US overtakes Australia to build biggest homes*. Available online: https://www.commsec.com.au/content/dam/EN/ResearchNews/Eco_Insights31.10_US_overtakes_Australia_to_build_biggest_homes..pdf.

Eicher, S., Hildbrand, C., Kleijer, A., Bony, J., Bunea, M. & Citherlet, S. (2014). Life cycle impact assessment of a solar assisted heat pump for domestic hot water production and space heating. *Energy Procedia 48*, 813-818.

Eicker, U. (2003). Solar Technologies for Buildings. John Wiley and Sons, Chichester.

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

Essential Services Commission (2015). Minimum Electricity Feed-in Tariff to Apply from 1 January 2016 to 31 December 2016: Final Decision, August.

Fischer, D., Wolf, T., Scherer, J. & Wille-Haussmann, B. (2016). A stochastic bottom-up model for space heating and domestic hot water load profiles for German households. *Energy and Buildings 124*, 120-128.

Fudholi, A., Sopian, K., Yazdi, M. H., Ruslan, M. H., Ibrahim, A. & Kazem, H. A. (2014). Performance analysis of photovoltaic thermal (PVT) water collectors. *Energy Conversion and Management 78*, 641-651.

Huang, S., Ma, Z. & Cooper, P. (2014). Optimal design of vertical ground heat exchangers by using entropy generation minimization method and genetic algorithms. *Energy Conversion and Management 87*, 128-137.

Kjellsson, E., Hellström, G., & Perers, B. (2010). Optimization of systems with the combination of ground-source heat pump and solar collectors in dwellings. *Energy 35*(6), 2667-2673.

Lhendup, T., Aye, L. & Fuller, R. J. (2014a). In-situ measurement of borehole thermal properties in Melbourne. *Applied Thermal Engineering 73*(1), 287-295.

Lhendup, T., Aye, L. & Fuller, R. J. (2014b). Thermal charging of boreholes. *Renewable Energy 67*, 165-172.

Matuska, T. and Sourek, B. (2013). Solar heat pump system with hybrid PVT collectors for a family house. *Central Europe towards Sustainable Building 2013.*

Mehrpooya, M., Hemmatabady, H., & Ahmadi, M. H. (2015). Optimization of performance of combined solar collector-geothermal heat pump systems to supply thermal load needed for heating greenhouses. *Energy Conversion and Management 97*, 382-392.

NatHERS (2012). Software Accreditation Protocol.

Putrayudha, S. A., Kang, E. C., Evgueniy, E., Libing, Y. & Lee, E. J. (2015). A study of photovoltaic/thermal (PVT)-ground source heat pump hybrid system by using fuzzy logic control. *Applied Thermal Engineering 89*, 578-586.

Standard Australia (2003)*: National Plumbing and Drainage: Part 4- Heated Water Services.*

Trading Economics (2016). *Australia Interest Rate*. Available online: http://www.tradingeconomics.com/australia/interest-rate.

Trillat-Berdal, V., Souyri, B., & Achard, G. (2007). Coupling of geothermal heat pumps with thermal solar collectors. *Applied Thermal Engineering 27*(10), 1750-1755.

TRNSYS (2016). The Transient Energy System Simulation Tool. Available online: http://www.trnsys.com.

Vieira, A. S., Beal, C. D. & Stewart, R. A. (2014). Residential water heaters in Brisbane, Australia: thinking beyond technology selection to enhance energy efficiency and level of service. *Energy and Buildings 82*, 222-236.

WaterFurnace (2016). Versatec Ultra NSKW Specification Catalog. Available online: http://www.geoexchange.com.au/download/WaterFurnace%20NSKW%2050HZ%20Aurora%20SC2566WN_Specification%20Catalogue.pdf.

Watmuff, J.H., Charters, W.W.S., & Proctor, D. (1977). Solar and wind induced external coefficients for solar collectors. Comples 2, 56.