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Investigation of Design and Control Strategies for Combining Photovoltaic Thermal (PVT) Solar Modules with Ground-Source Heat Pump Systems: Case Example for Net Zero Building in a Moderately Cold Climate

Sulaiman Almoatham **Andrew Chiasson** **Rydge Mulford**
Mariana Moreno-Pena **Cy Yavuzturk** **Roshan Revankar**
Steve Hamstra **Micah Zender** **Steve Melink**

ABSTRACT

A synergistic coupling of a ground source heat pump (GSHP) system with photovoltaic thermal (PVT) modules for a cooling dominated net-zero building in a moderately cold climate is presented in this study. As individual systems, GSHP and PVT systems have experienced sluggish market penetration; GSHP systems have relatively high capital cost compared to conventional heating and cooling systems, while PVT systems have niche applications mainly limited to swimming pool heating in moderate to cold climates. Coupled together, the design of the holistic system is non-unique; the ground heat exchanger (GHX) could be designed to optimize efficiency of the PV cells, or the PVT array could be designed for thermal management of annual ground thermal load imbalances on the ground heat exchanger (GHX), or some combination of these design approaches. Given the non-unique design approach for these coupled systems, this study examined various design, control, and operating strategies through hourly simulation software (TRNSYS) for a 20-year life cycle of the system of an actual zero-energy building in a moderately cold climate, which is quite cooling-dominated owing to its superior envelope design. The PVT design and control strategies were aimed at reducing the size of the GHX versus improving the electrical production of the PV. The investigated control strategies found that it is possible to reduce the size of the GHX by 40%, and increase PV electrical energy production by 5%. The control strategy of using nocturnal cooling by the PVT to unload stored thermal energy from the GHX achieved the lowest life-cycle cost. The nocturnal monthly cooling energy unloaded varied between 30 and 140 kWh/m² for summer and winter months over the 20 years of simulation period.

INTRODUCTION

Widespread electrification of the built environment is a key societal component toward achieving carbon neutrality. However, space heating and cooling energy is responsible for 55% of the residential and commercial buildings energy consumption, and the building sector accounts for one third of the global energy use and greenhouse gas emissions (IEA (2020)). Heat pumps offer a solution toward efficiently electrifying space heating needs, but moving toward a fully electric grid utility system increases peak electricity supply requirements. Use of photovoltaic (PV) systems

Sulaiman Almoatham (almoathams1@udayton.edu) is a Doctoral Candidate at the University of Dayton and a lecturer in the Department of Mechanical Engineering, Prince Sattam bin Abdulaziz University. Andrew Chiasson is an Associate Professor, Rydge Mulford is an Assistant Professor, and Mariana Moreno-Pena is undergrad student in the Department of Mechanical & Aerospace Engineering, University of Dayton. Cy Yavuzturk is a Professor of Mechanical, Aerospace, and Acoustical Engineering, University of Hartford. Roshan Revankar is a Project Engineer, Steve Hamstra is Senior Vice President of Engineering, Micah Zender is Product Development Manager, and Steve Melink is President of Melink Zero.

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is an obvious choice for on-site electricity production in buildings, but energy production is low in northern winter months. Ground-source heat pump (GSHP) systems, as one of the most energy-efficient heating and cooling technologies currently available, are viable to support building decarbonization by mitigating the overall costs and impacts of space heating, but larger scale market uptake remains hindered by their high capital costs and long payback periods, particularly in buildings with unbalanced annual loads that require prohibitively large ground heat exchangers.

Many energy-efficient buildings may combine PV systems with GSHP systems, but using a photovoltaic-thermal (PVT) system for thermal management of a GSHP system is far less common. Coupled to a building with a superior envelope, PVT-GSHP systems have potential to cost-affordably achieve net-zero energy in the built environment. The challenge in the design of these systems lies in optimizing the size of the PVT and ground heat exchanger (GHX); a GHX size could be optimized to cool PVT modules, thus increasing PV production, or the PVT size could be optimized to heat or cool the GHX, thus minimizing the GHX size and cost. Alternately, both subsystems could be optimized to achieve lowest life-cycle cost.

The following is a review of the current state of the literature regarding GSHP thermal imbalance issues and hybrid GSHP systems, and the use of the PVT array.

Ground-source heat pump (GSHP) systems have gained acceptance as clean, efficient, and life-cycle cost-effective technology used for space heating and cooling. GSHP systems use the relatively stable temperature of the Earth as a heat source and/or sink, which results in significant energy savings compared to conventional HVAC systems. However, when thermal loads on the GHX are not balanced over the annual cycle, the underground temperature tends to increase (in cooling-dominated applications) or decrease (in heating-dominated applications) over the life cycle of the system, which results in the necessity to design large, cost-prohibitive GHX (Georgiev et al. 2020; Yavuzturk and Spitler 2000) . Alternatively, hybrid GSHP systems utilize a supplemental heat rejection/generation component to offset some portion of the thermal load on the ground, thereby reducing the size and capital cost of the GHX. Many supplemental components have been studied in the literature, such as cooling towers, boilers, and solar collectors (Chiasson 2016).

Hybrid GSHP system design for cooling-dominated buildings utilizing cooling towers is the subject of much of the scientific literature. For example, several hourly simulation studies were developed to determine the lowest life cycle cost of various operation and control strategies for hybrid GSHPs with cooling towers (Yavuzturk and Spitler 2000; Yi et al. 2008; Hackel et al. 2009; Hackel, S., Pertzborn 2011).

Hybrid solar GSHP systems have been intensely studied for heating-dominated buildings. For example, Chiasson and Yavuzturk (2003) studied the performance of solar thermal collectors coupled with GSHP for a heating-dominant school in the northern US. The solar collectors were used to recharge the ground which resulted in GHX reduction between 4.5 m per m^2 and 7.7 m per m^2 of solar collectors. In experimental work, Georgiev et al. (2020) examined hybrid solar-GSHP for a small house in Bulgaria. They found that solar charging of the boreholes resulted in a 1-2℃ increase in the temperature of the borehole, which prevented ground temperature depletion and offset the ground temperature decrease due to the GSHP heating operation.

Hybrid solar GSHP systems for cooling-dominated applications have been rarely investigated, but some published studies do exist. For example, Lhendup et al.(2012) tested the performance of an inter-seasonal cool storage system consisting of two solar collectors and two GHXs, where one GHX was used for high-temperature thermal energy storage and the other for cool temperature thermal energy storage. Heat was rejected through the longwave thermal radiation exchange between the unglazed collector and the sky at night. Their experiment resulted in 0.5℃ ground temperature reduction and 120 W/m^2 of cooling by the solar collectors during 80 days of the experiment.

The potential of nocturnal cooling of typical PVT panels has been tested by Hu et al. (2020). Their experiment suggested that it is possible to cool the PVT plate temperature by up to 9℃ below the ambient temperature (Hu et al. 2020). Furthermore, Eicker and Dalibard (2011) have tested the nocturnal cooling of PVT modules in a residential zero energy building in Madrid, Spain. Their system was able to achieve 60 – 65 W/m² of cooling when the PVT collector was used to cool a warm storage tank, and 40 – 45 W/m² of cooling when the thermal energy was directly used to cool a ceiling.

This article aims toward evaluating the optimal design and operating strategy of GSHP systems integrated with solar PVT array in a net-zero cooling-dominated building in a cold climate.

The objectives of this research are to: (1) examine the effect of various control strategies of the hybrid system on the GHX size and the PVT performance; (2) optimize the GHX size using the nocturnal cooling effect of the PVT array as the objective function; and (3) evaluate the economic viability of the hybrid system with a 20-year life-cycle cost analysis.

METHODOLOGY

The following sections describe a potential hybrid GSHP-PVT system connected to an existing net-zero building in Cincinnati, Ohio. Models to predict the performance of the standalone GSHP, PV systems, and hybrid GSHP-PVT system were developed in the TRNSYS modeling environment for hourly simulation. The simulation was used to study the effect of four different control strategies of the hybrid system on the size and the performance of the GSHP and PVT, allowing an economic analysis to be conducted.

System description and control strategies

GSHP systems reject heat to the ground in cooling mode or extract heat from the ground in heating mode. Owing to the large time constant of the Earth, the heat pump entering fluid temperature (EFT) increases or decreases over time. For this simulation, the GHX was sized to maintain the maximum and minimum EFT at 35℃ and 0℃ within the simulation period (20 years). A representative schematic of the system built in the TRNSYS modeling environment is shown in Figure 1.

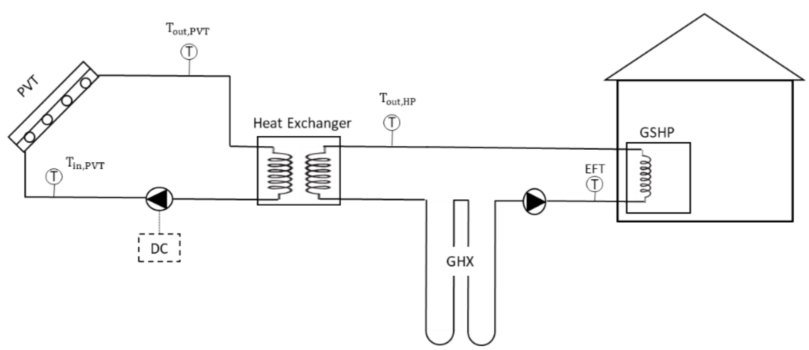


Figure 1. Schematic diagram of the hybrid system.

Four possible system control strategies are listed in Table 1. The control strategies are designed to either extract or reject heat to reduce the size of the GHX or to increase the efficiency of the photovoltaic panels. The first control strategy reduces the GHX size by using radiative losses from the PVT panels to cool the GSHP loop during non-sun hours, rejecting excess heat from the ground. The second control strategy improves the PV efficiency by cooling the PVT loop with the heat pump exiting fluid using the GHX as a heat sink. However, cooling the PV loop doesn't necessarily increase the efficiency at all the times, compared to reference PV, due to the high heat pump exiting temperature, especially during summer. Thus, the third control strategy will ensure an efficiency improvement by allowing the fluid to run through the PVT only if it is less than the PV cell operating temperature. The last control strategy combines both improving the PV efficiency and reducing the GHX size by cooling the PV array during the day and cooling the GHX during the night, thereby running the system pump continuously. The control strategies were simulated using a differential controller (TRNSYS Type 911). The controller monitors the PVT outlet temperature ($T_{out,PVT}$), heat pump exiting fluid temperature ($T_{out,HP}$), PVT inlet temperature ($T_{in,PVT}$), and PV cell temperature ($T_{cell,PVT}$). The differential control temperature selected was 3°C.

Table 1. System control strategies

CS*	Objective	Control
CS#1	Reduce number of boreholes	Run the PVT loop pump if ($T_{out,HP}$ - $T_{out,PVT}$) > 3°C
CS#2	Increase PV efficiency	Run the PVT loop pump if ($T_{out,PVT}$ - $T_{out,HP}$) > 3°C
CS#3	Increase PV efficiency	Run the PVT loop pump if ($T_{cell,PVT}$ – $T_{in,PVT}$) > 3°C
CS#4	Cool the PV array during day Cool the GHX during night	Run the PVT loop pump continuously

* Hybrid GSHP-PVT Control Strategy

Sub-systems

Building loads and description

The building used for this study is an existing two-story, small office building located in southwestern Ohio, USA, and was designed for net-zero energy use. The building has 2,790 m^2 of conditioned floor space with a super-insulated envelope comprised of R30 (RSI 5.3) walls (insulated with spray foam), and R50 (RSI 8.8) roof (constructed of multi-layered foam board). High-performance window and door systems are included in the design for maximum daylighting, minimum heat gain in the summer and heat loss in the winter. Electrical loads are minimized through the use of smart LED lighting with occupancy sensors and dimming control. Additionally, the building utilizes innovative hydronic heating and cooling with heat pumps, auxiliary heat sinks/sources, and a thermal battery to minimize electric demand during both summer and winter conditions. A solar PV system is used as a parking lot canopy to produce clean energy for the building and electric cars connected to the system. EV chargers were included in 80% of the parking spaces. Although the building is located in a mixed-humid/cold climate (2700 heating degree day (18°C base)), the high-performance building envelope results in an annual cooling to heating load ratio to be around 6, which is a load profile more common to a much warmer climate zone. The thermal peak cooling and heating loads of the building are 129 and 96 kW, respectively. The building's total annual energy cooling and heating are 142,159 and 23,849, respectively. The building loads profile is shown in Figure 2. The annual, maximum, and minimum air temperature of location are 12 ℃, 41 ℃, and -27 ℃. The annual average relative humidity is 78%.

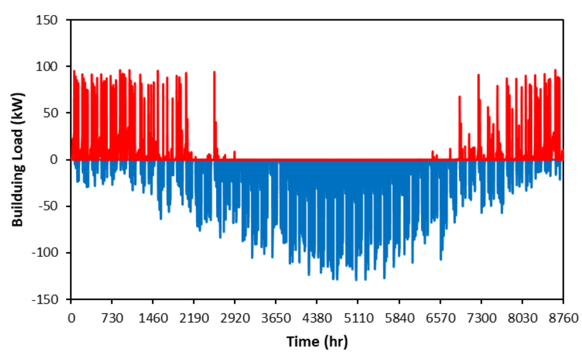


Figure 2. Hourly heating loads (positive) and cooling loads (negative) for the example building.

Photovoltaic Thermal (PVT), Ground Heat Exchanger (GHX), and Heat pump (HP)

A PVT component model was developed and added to the TRNSYS library for this work. The thermal collector efficiency is determined using Equation 1 (Burch et al. 2004):

$$\eta = F_R(\tau\alpha) - F_R U_L \times \frac{T_i - T_{amb}}{G_{net}} \quad (1)$$

Where the terms Fr, U_L, T_i, T_{amb} are the heat removal factor, heat loss coefficient, fluid inlet temperature, and ambient temperature, respectively. The net incident radiation, G_{net}, includes both the total solar radiation, G_{sun}, and the infrared radiation from the PVT plate to the sky, G_{sky}, as given in Equation 2 and 3.

$$G_{net} = G_{sun} - \left(\frac{\varepsilon}{\alpha} G_{sky}\right) \quad (2)$$

$$G_{sky} = \sigma \left({T_{cell}}^4 - {T_{sky}}^4 \right) \quad (3)$$

where σ is Stefan-Boltzman constant, T_{cell} is the PV cell temperature, and T_{sky} is the effective sky temperature given as a function of dew point temperature, cloud cover, atmospheric pressure, and time of the day. The effective sky temperature is calculated using the Martin and Berdahl (1984) correlation. The PVT modules used in this simulation have an area of 1.45 m^2, electrical effiecincy of 13.6%, heat removal factor ($F_R\ \tau\alpha$) of 0.6, and heat loss slope ($F_R U_L$) of 15 ($W \cdot m^{-2} \cdot K^{-1}$). Each collector has flow rate of 108 ($kg \cdot h^{-1}$). The derating factor which includes shading, dust accumulation, wiring losses was assumed to be 85%. Also, the power degradation was assumed to be 0.5% per year.

Simulation of the GHX performance is accomplished with TRNSYS component Type 557. The ground and grout thermal conductivity was assumed to be 2.1 and 2.4 ($W \cdot m^{-1} \cdot K^{-1}$), respectively. Each borehole has a radius of 0.127 m and a borehole spacing of 7 m. The peak design volumetric flow rate is 2.5 L/min per kW of peak building load.

A component model describing the performance of water-to-air geothermal heat pumps has been developed for hourly GSHP system simulations. Inputs to the heat pump model include the thermal loads, entering fluid temperatures, and fluid mass flow rates. Dynamic modeling of the heat pump load side involves imposing the building loads on the heat pumps, and thus zone temperatures were not explicitly modeled. Linear curve-fit equations to manufacturer's heat pump catalog data are employed to compute the heat rejection in cooling mode, heat absorption in heating mode, and the heat pump energy consumption as a function of the heat pump source entering fluid temperature. Outputs provided by the models include exiting fluid temperature, energy consumption, fluid mass flow rate, and heat pump COP. For this work, the heat pump heating COP was modeled to vary linearly from 4.0 to 5.0 at entering source temperatures ranging from 0°C to 20°C, respectively. The heat pump cooling COP was modeled to vary linearly from 7.0 to 4.5 at entering source temperatures ranging from 10°C to 32°C, respectively.

Economic analysis

The economic performance of the standalone GSHP and the hybrid system was compared using the total cost of ownership (TCO) which is the net present value of the capital cost, operation cost, and operation saving over the 20 years simulation period. The operation cost includes the heat pump electricity consumption and the PVT pump electricity consumption, and the operation saving includes the PV electricity generation. TCO's were calculated assuming an 8% discount rate, $50/m drilling cost (which includes all underground work), $0.12/kWh electricity price, $2.7/W PV cost, and $4/W PVT cost (BRE National Solar Centre and Delta-ee 2016).

RESULTS AND DISCUSSION

Performance of standalone GSHP and PV reference systems

The standalone GSHP system required 2800 m (28 x 100 m) of borehole length to meet the heat pump entering fluid (EFT) design over the 20-year simulation period. Moreover, standalone PV system analysis was performed as a reference for comparison with the electrical production of the PVT in the hybrid system. This simulation used 13.8 kW (100 m^2) of PV for all the analyses. The PV system size was not designed to cover the building electricity load but was determined where the maximum GHX length reduction is possible. The PV resulted in an average of 15,567 kWh per year of energy production.

Performance of the hybrid system with the control strategies

The first control strategy reduced the required boreholes field by 40% by extracting the thermal load from the GHX. This strategy did not improve the PV production since it runs mostly during the night. On the contrary, the second and third control strategies improved the annual PV production by 4.56% and 3.84%, respectively, while increasing the GHX length by 7% and 4.6%, respectively. The best PV performance improvement was by the last control strategy where the PVT loop is running continuously to charge and recharge the ground alternately. It improved the annual PV production by 5.26% while decreasing the borehole length by 35%. The heat pump consumption was within 4% for all cases. Table 2 summarizes the hybrid system performance under different control approach. The presented values are then averaged over the 20 years simulation period.

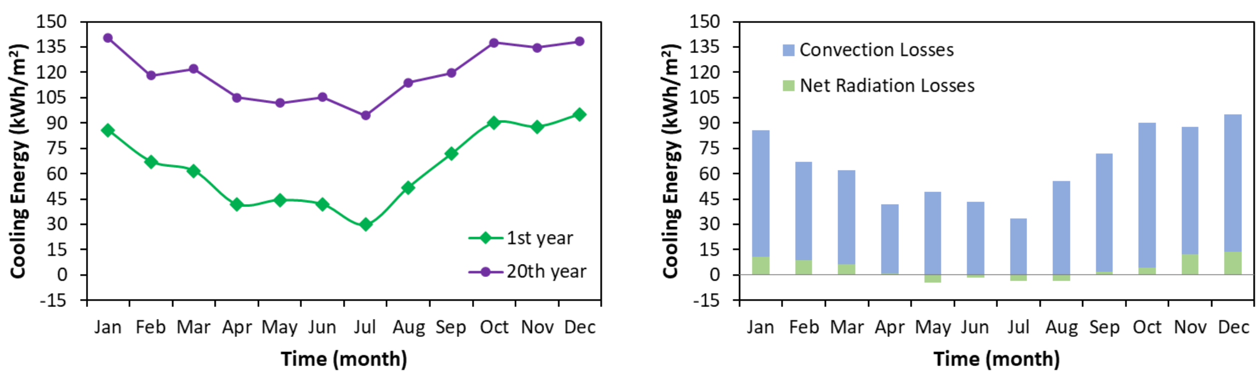
Table 2. hybrid system performance under different control strategies

System	Borehole length	HP consumption (kWh/year)	PVT electrical production (kWh/year)	PV production difference	PVT pump consumption (kWh/year)
Standalone GSHP	28 x 100 (2800 m)	32,553	-	-	-
Standalone PV	-	-	15,567	-	-
Hybrid GSHP-PVT CS#1	17 x 100 (1700 m)	31,220	15,569	0.01%	5,882
Hybrid GSHP-PVT CS#2	30 x 100 (3000 m)	32,732	16,277	4.56%	2,129
Hybrid GSHP-PVT CS#3	29 x 101 (2929 m)	32,729	16,165	3.84%	1,170
Hybrid GSHP-PVT CS#4	19 x 96 (1824 m)	31,678	16,386	5.26%	9,636

Nocturnal cooling effect on the GHX

The first control strategy was aimed at reducing the length of the boreholes by rejecting heat during the night using the PVT. The nighttime cooling was effective in offsetting some of the ground loads and reducing the GHX length. Through iterative optimization of the system, it was possible to reduce the length of the total borehole by 40% with 100 m² of PVT. The borehole length reduction was maximized with PVT solar collector array size of 100 m² (13.8 kW).

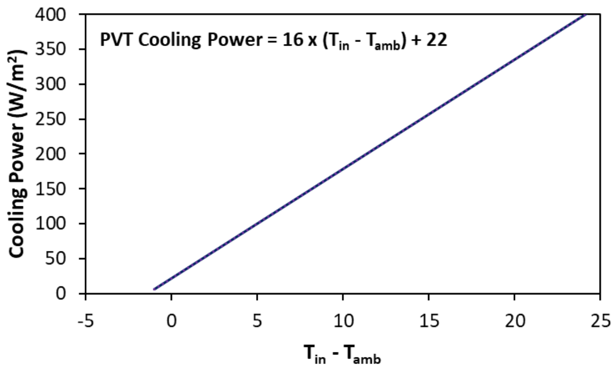
Figure 3a shows the monthly cooling energy of the PVT collectors for the 1st and 20th year of the simulation. Figure 3b also shows a monthly breakdown of the convective and radiative losses. The cooling energy increased over the years due to the gradually increasing GHX temperature. The average annual cooling energy of the PVT was 64 and 119 kWh/m² for the 1st and 20th year, respectively, with a variation between 30 and 140 kWh/m² for the summer and winter months. Furthermore, the convective losses dominated the losses due to the cold climate of the location. It is interesting to note that the net radiation losses are negatives in summer because it included both the short and the longwave radiation as described by Equation 2.



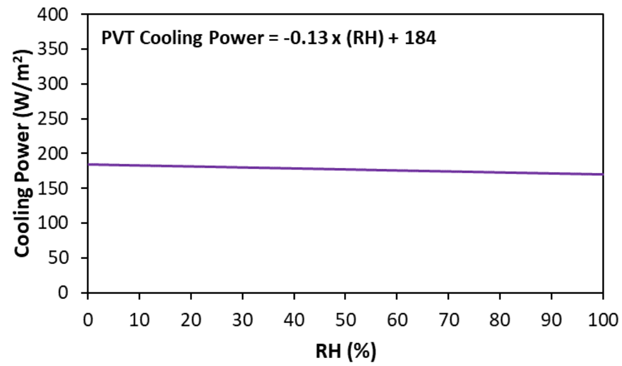
(a) (b)

Figure 3. (a)1st and 20th year's monthly cooling energy (b) monthly breakdown of the convective and radiative losses.

The fitted curve of the PVT modules cooling power with a temperature difference between inlet fluid and ambient air temperature is shown in Figure 4a. The cooling power increases nearly linearly with the increase of the temperature difference. The fitted curve relation of the cooling power with temperature difference is expressed as: 16 x ($T_{in} - T_{amb}$) + 22. Conversely, the PVT modules cooling power decreased with the increase of the relative humidity as shown in Figure 6b. The fitted curve relation of the cooling power with relative humidity is expressed as: -0.13 x (*RH*) + 184.



(a)



(b)

Figure 4. Fitted curve of PVT cooling power with: (a) inlet and ambient temperature difference (b) relative humidity.

Economic analysis

An economic analysis was performed to evaluate the hybrid system with each of the control strategies, and results are summarized in Table 3. The total capital cost of hybrid GSHP-PVT system control strategies 1 and 4 are close to the cost of the standalone GSHP with the additional benefit of PV electrical production. The systems with control strategies 2 and 3 produce electricity but increase the cost by approximately 45% compared to the standalone GSHP and 15% compared to the standalone GSHP with PV system. Thus, the total cost of ownership over 20-years is the lowest for a hybrid system with control strategy 1. It is followed by the hybrid system with control strategy 4 and the standalone GSHP. In addition, compared to the standalone GSHP, the hybrid system control strategies 1 and 4 reduced the TCO by 7.17% and 1.45%, respectively, while the hybrid system control strategies 2 and 3, and the standalone GSHP with PV system increased the TCO by 27.33%, 24.78%, 10.61%, respectively.

Table 3. Summary of the economic analysis.

System	GSHP		PV/T			Total		
	Capital Cost ($)	Annual HP Energy Consumption ($/year)	Capital Cost ($)	Annual PV Production ($/year)	Annual Pump Energy Consumption ($/year)	Capital Cost ($)	Cost of Ownership ($)	TCO Difference (%)
Standalone GSHP	140,000	3,906	-	-	-	140,000	178,354	-
Standalone GSHP + PV	140,000	3,906	37,260	1,868	-	177,260	197,273	10.61%
Hybrid system CS#1	85,000	3,746	55,200	1,868	706	140,200	165,570	-7.17%
Hybrid system CS#2	150,000	3,928	55,200	1,953	255	205,200	227,095	27.33%
Hybrid system CS#3	146,450	3,927	55,200	1,940	140	201,650	222,544	24.78%
Hybrid system CS#4	91,200	3,801	55,200	1,966	1,156	146,400	175,770	-1.45%

CONCLUSION

Various operational strategies of the hybrid GSHP system coupled with PVT collectors are proposed in this study as an attempt to reduce the GHX size and increase the PV efficiency for a net-zero building in a moderately cold climate. The main findings were:

- Nocturnal cooling using the PVT built into the hybrid system was capable of reducing GHX size by up to 40% compared to the standalone GSHP system.
- Using the ground to cool the PV panels increased the PV production by between 3.86%- 5.86% depending on the control strategy. However, it also increased the size of the GHX.
- Using the PVT loop to extract heat from the GHX features the lowest TCO followed by operating the PVT loop continuously throughout night and day. The TCO of the system is mostly driven by the upfront cost of the GHX boreholes.
- The average annual cooling energy provided by the PVT is 64 and 119 kWh/m^2 for the 1st and 20th year, respectively.
- The monthly cooling energy varied between 30 and 140 kWh/m^2 for the summer and winter months over the 20 years of the simulation period.

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