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Performance Analysis of Hybrid Ground Source Heat Pump and PVT System for Nordic Climate

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Abstract

During the past few years, Ground Source Heat Pump (GSHP) systems have attracted great attention because of the ability to improve the efficiency compared to air source heat pumps (AHSP), especially in cold climates. This paper aims to evaluate the performance of a GSHP system with series-connected solar PVT collectors for a Multi Family House (MFH) in the heating-dominated region of Oslo, Norway. The system efficiency has been obtained by a detailed simulation of the system model for 50 years using TRNSYS software. The results indicate that using the PVT collectors can significantly influence the Seasonal Performance Factor (SPF) of the system by maintaining the ground temperature compared to the case without PVT. In addition, a parametric study has been carried out to investigate how much the number of the boreholes can be reduced by adding PVT to the system while maintaining the same SPF as a standard GSHP. Hybrid systems combining GSHP and PVT collectors have the potential to contribute to the decarbonization of the MFHs in dense urban areas and to achieve Zero Energy Buildings (ZEB) in Europe.

Keywords: Solar assisted heat pump; Ground source heat pump; PVT; Solar energy; Thermal energy strorage

1. Introduction

The building sector accounts for approximately 40% of the world's energy consumption [1]. Furthermore, space cooling, space heating and Domestic Hot Water (DHW) takes a large proportion of buildings energy consumption, commonly 40-60%, depending on the climate and the type of the building [2]. Also, improving the life standards results in increasing the energy consumption of the buildings during the next years. Therefore, energy saving and further developing the current Heating, Ventilation and Air Conditioning (HVAC) systems play an important role in decreasing the world's total energy consumption.

Heat pump is an energy efficient technology which can be used for heating and cooling purposes. This technology is of interest since it consumes less electricity and primary energy compared to traditional heating systems, such as electric heaters and boilers. There exist different types of heat pumps based on the heat source of this system, such as air-source [3], water-source [4] and ground-source heat pumps [5]. Air-source heat pumps are the most common types in Norway and the main advantage of these heat pumps is the lower electricity consumption in comparison with direct electric heaters. They can be used for both cooling and heating and operate even while the ambient temperature is as low as -20 °C. The performance of these systems strongly depends on the ambient temperature, since by decreasing the source-side temperature of the heat pumps, the electrical energy consumed by the compressor increases considerably, which results in reducing the coefficient of performance (COP) of the whole system [6]. Therefore, using another source of thermal

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energy which can provide relatively higher and constant temperature during the year is beneficial for enhancing the system performance [7].

Ground Source Heat Pumps (GSHP) can be considered as a good solution, since these systems benefit from the high quantity of thermal energy, which is stored in the ground, and can compensate the low ambient temperature [8, 9]. Solid ground, seawater, soil ground and groundwater can be used as the heat source of GSHP systems. In Norway, the majority of GSHP installations are indirect closed-loop systems utilizing vertical boreholes in crystalline rock [10]. Using this technology, the effect of outdoor air temperature fluctuations on the performance of the system will be reduced, since the ground temperature remains relatively constant throughout the year. One of the main limitations regarding the use of GSHP systems for a region dominated by heat extraction is decreasing ground temperature after a couple of years. Depending on the borehole size and the heating demand, the average temperature of the soil may decrease by 0.5 to 1 °C each year, which results in decreasing the COP of the system after a few years [11]. This reduction in ground temperature can be reduced by increasing the borehole depth and borehole number. It should be noted that increasing the borehole depth is associated with considerable rise in drilling costs and also, increasing the number of boreholes requires large area. The thermal load of Multi Family Houses (MFH) is dominated by heating in Norway. The vast majority of MFHs are located in highly dense locations of urban areas where land for drilling a large borehole field may not be available. Therefore, another solution for maintaining the ground temperature throughout the lifespan of the GSHP should be considered.

One of the methods for overcoming this problem is using the solar heat for regenerating the boreholes by storing the absorbed solar energy during the summer. In this research, the aim is to study the performance of a Solar-Assisted Heat Pump (SAHP) system in heating dominant regions with high latitude, such as Norway. During the conversion of the solar radiation into electricity using a PV module, the surface temperature of the panel increases, which leads to decrement of solar panel efficiency. Therefore, cooling the surface temperature of the panel, which can be conducted using water or air, is necessary to maintain the efficiency. Hence, the concept of PVT collectors has been introduced to enable the potential of reducing the panel temperature to keep the electrical efficiency at a satisfactory level and at the same time, absorb the thermal energy from the received solar radiation by the collector. In other words, these collectors are a hybrid between photovoltaic (PV) and solar thermal panels, which produce electricity and heat, respectively.

Noro et al. [12] studied the energy and economic performance of using PVT panels coupled with an electric compression heat pump to provide space heating in different climates. The results of this study show that up to 65% reduction in primary energy can be achieved by using this hybrid system and also, the discounted payback of the investment can be around 10 years. Lazzarin et al. [13] investigated the effect of using a hybrid system of GSHP-PVT for a refurbished building and optimized the sizing of the system by considering five alternatives, increasing the solar field from 20 m^2 to 60 m^2 and reducing the ground field from 500 m to 300 m. The dynamic simulation of this study reveals that the most efficient alternative for this system is the case with 60 m^2 PVT combined with boreholes of 300 m. Sommerfeldt et al. [6] carried out a parametric study of the technical and economic performance of GSHP-PVT system for a MFH located in Sweden. The results of this study show that using PVT modules can result in reducing the borehole length by 18% and maintaining the SPF of the system compared to the case without PVT.

In this work, PVT collectors are used for the thermal regeneration of the boreholes while they are not operated for heating purposes. TRNSYS, which is a dynamic simulation software, is used for simulating the PVT-GSHP system. The main objective of this paper is to investigate the energy performance of GSHP system combined with glazed and unglazed PVT collectors for a MFH in Oslo. The heating system provides both Space Heating (SH) and Domestic Hot Water (DHW) and is designed in such a way that producing DHW is prioritized over SH when both demands occur at the same time. Moreover, a sensitivity analysis has been carried out to study the effect of using different number of boreholes. The performance of a GSHP with a reduced number of boreholes combined with PVT collectors (to compensate the temperature reduction after some years of operation) is compared to a standard GSHP without PVT.

2. Model description

In this work, the simulation of a GSHP system for providing SH and DHW for a MFH is presented. The simulated building is a four-story MFH with net floor area of 420 m^2 per each floor which has the characteristics of a Norwegian building constructed between 1991 to 2000, i.e., generation 5 in [14]. The heating system designed for this building includes a combined PVT-GSHP system and direct electric heaters for covering the peak load. The simulation is carried out using the dynamic simulation software, TRNSYS 17, with time step of 2 min for the whole period of the study, which is 50 years.

In order to recharge the extracted heat from the ground a series/regenerative system is used, where the PVT loop is connected to a plate heat exchanger on the evaporator side of the heat pump. In this configuration, when the heat pump is on, the PVT boosts the borehole loop temperature and when the heat pump is off, the PVT regenerate the ground. The schematic overview of the system is shown in Figure 1.

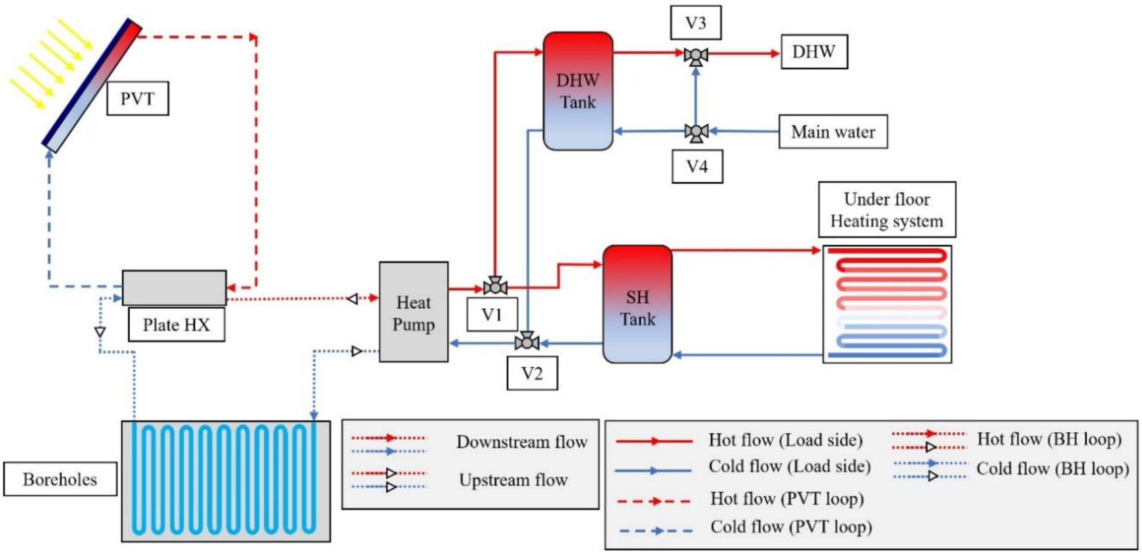

Fig. 1. Base scheme of PVT+GSHP in series/regenerative mode.

The meteorological data has been obtained from Meteonorm Software. The Norwegian standard for calculation of energy needs and energy supply (SN-NSPEK 3031: 2021) [15] has been used to define the internal gains by people, lights and equipment, infiltration rate, ventilation rate and Domestic Hot Water (DHW) demand. Since the building is located in a heating dominant region, there is no need for cooling and only heating is required. Based on Norwegian standards, the set point temperature for heating the residential buildings is 20 °C for the night and 22 °C during the day and 55 °C for DHW. Figure 2 shows the hourly variation of heat generated by internal gains and heating demand for DHW according to [15].

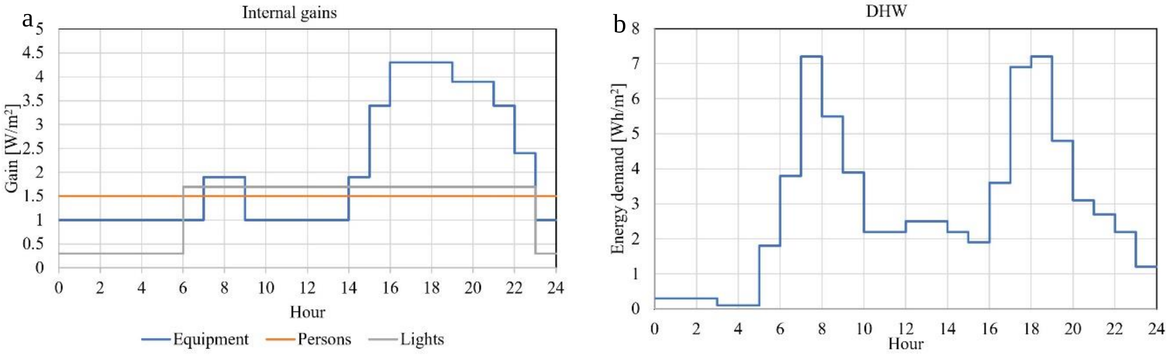

Fig. 2. Hourly variation of a) heat generated by internal gains and b) heat required for DHW.

The yearly simulation gives an annual and specific energy demand for heating of the building by 179 MWh/year and 107 kWh/(year.m^2), respectively. Figure 3 shows the monthly SH and DHW demand during the year. Also, the maximum power required for providing both SH and DHW is 104 kW.

Simulations has shown that a HP covering 70% of the peak power results in a large energy coverage factor., Therefore a water-to-water single-speed heat pump with total heating capacity of 69.44 kW has been chosen. The HP is expected to cover approximately 90% of the energy demand of the building and the remaining comes from direct electric heaters, which can cover the peak load. Three different layouts have been used to provide the required heat for the building, including the standard GSHP system, GSHP-glazed PVT and GSHP-unglazed PVT. The heating system provides both SH and DHW and is designed in such a way that producing DHW is prioritized over SH when both demands occur at the same time. In this study, the baseline model comprises 12 single U-shape and water-filled non-grouted boreholes of 200 m depth with spacing of 20 m. The PVT collectors used for the study have the PV efficiency of 17.02% at reference condition with a temperature coefficient of -0.0041 (1/K). Two different numbers of PVT collectors have been used which correspond to area of approximately 50 m^2 and 100 m^2.

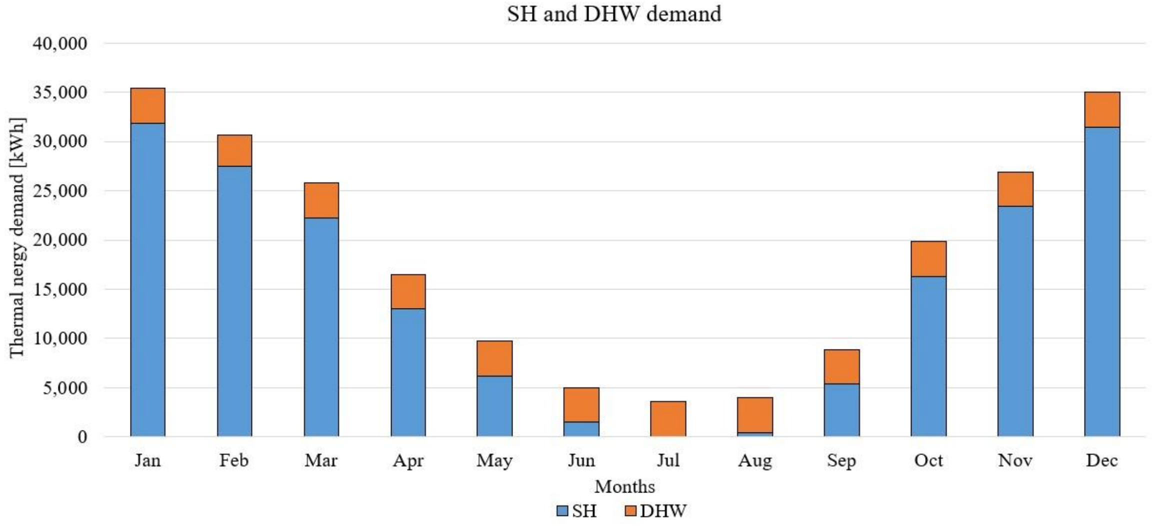

Fig. 3. Monthly SH and DHW demands of the building.

In the standard GSHP layout without PVT, only heat extraction from the boreholes occurs, which results in reducing the borehole temperature after some years of operation. In GSHP-PVT layout, the recharge of the ground temperature occurs when the outlet temperature from the PVT collector is high enough to be able to recharge the borehole. In this study, the PVT circuit turns on when the temperature difference between the outlet of the PVT and inlet of the plate heat exchanger is higher than 6 K. Also, two different modes for GSHP with PVT systems have been used. In downstream mode, the outlet flow from the borehole enters the plate heat exchanger and absorbs thermal energy from the PVT loop, and then enters the evaporator side of the HP. In upstream mode, the flow direction in BH loop has been reversed and the outlet of the BH flows directly to the evaporator side of the HP and then, the outlet from the HP flows into the plate heat exchanger to be recharged by the PVT loop.

The Key Performance Indicators (KPIs) used for assessing the performance of the system are as follows:

$$SPF = \frac{Q_{H,HP}}{E_{Comp}} \tag{1}$$

$$SPF_4 = \frac{Q_{SH}+Q_{DHW}}{E_{Comp}+E_{Aux}+E_{Pumps}} \tag{2}$$

Where SPF is the Seasonal Performance Factor for the HP, $Q_{H,HP}$ and E_{Comp} are heat delivered by the condenser and electricity consumed by the HP, respectively. SPF_4 is the performance factor of the whole system which is equal to the ratio between the heat delivered for SH and DHW over the electricity consumed by the HP, auxiliary heaters and the pumps in the system. SPF_4 also takes into account the thermal losses of the two hot-water storage tanks.

3. Results and discussion

In this section, the results from the long-term performance analysis of the combined GSHP-PVT system are presented. Figure 4 shows the electricity consumption of each component in the standard GSHP system. Based on this chart, since the HP system cannot cover all the heating demand of the building, a significant amount of electricity is consumed by the auxiliary heaters to cover the peak load in January, February and December. The amount of energy consumed by the peak load system increases after some years of operation, since the heat provided by the HP decreases gradually with the decreasing ground temperature.

Figure 5 shows the average BH temperature (T_m) of the standard GSHP system with 12 BHs. In this system, since there are no other energy resources to recharge the extracted thermal energy from the BHs, a significant reduction in the average BH temperature can be seen. This reduction can result in a considerable reduction in the performance of the HP system. Figure 6 shows the yearly variation of SPF and SPF_4 of the same system with and without PVT collectors in the period of 50 years. Based on this figure, it can be seen that the SPF and SPF_4 decrease as a result of decreasing the outlet BH temperature, but in case of using PVT collectors, since a part of extracted heat from the ground can be recharged, less reduction in SPF and SPF_4 is observed.

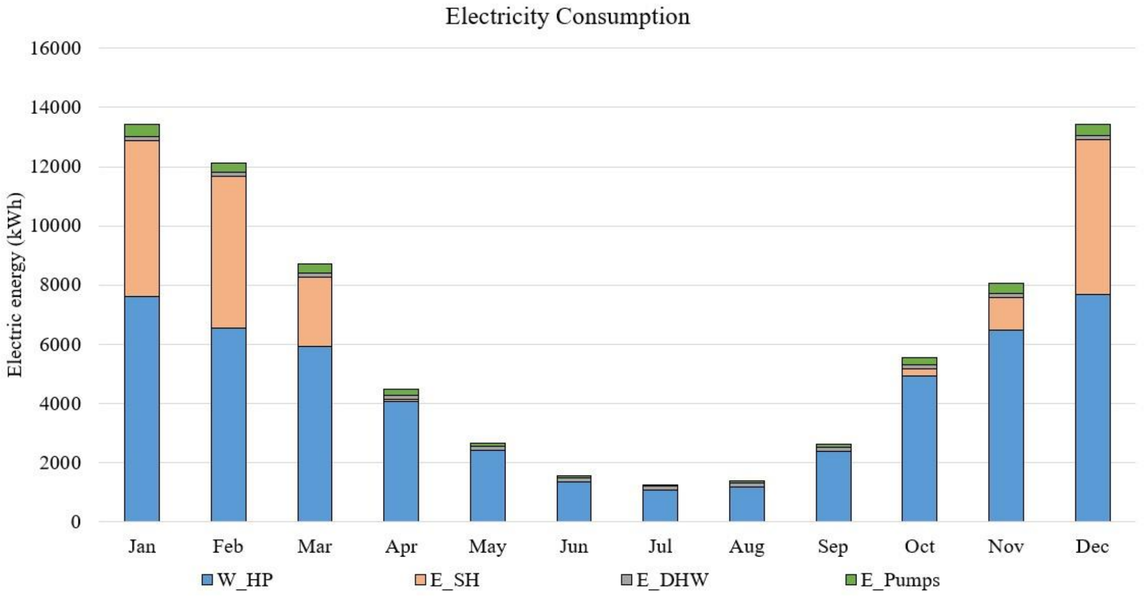

Fig. 4. Monthly electricity consumption of the heat pump and auxiliary heaters in GSHP system with 12 BH.

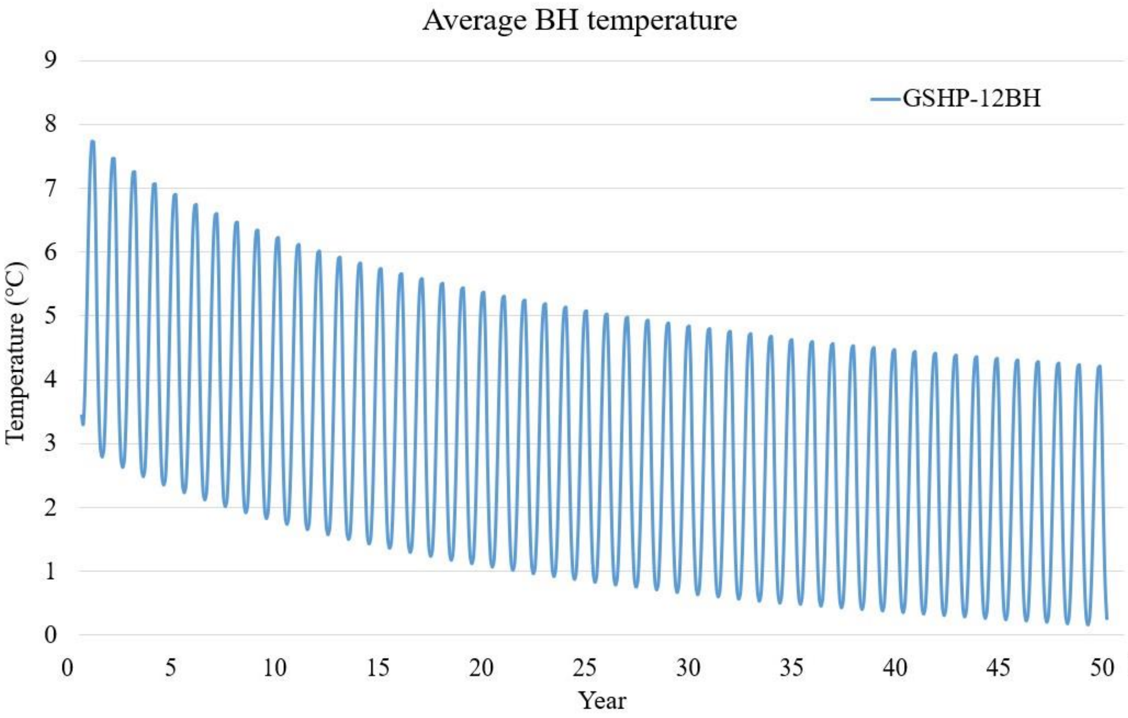

Fig. 5. Variation of average fluid temperature for GSHP simulation with 12 BH in 50 years.

The reason for reducing the SPF_4 of the system after some years of operation can be better seen in Figure 7. According to this figure, the percentage of heat provided using the HP reduces as the result of reducing the BH temperature. This reduction results in increasing the percentage of the heat provided using the peak load system, which subsequently leads to decreasing the SPF_4 of the system.

In Figure 6, the GSHP-PVT system has downstream layout with unglazed PVT collectors. Since the glazed PVT collector has higher thermal efficiency, the same case study has been investigated using the glazed collectors to study the effect of BH temperature reduction and consequently reduction in SPF and SPF_4 using these PVTs. It should be noted that since the glazed PVT collectors typically can produce higher temperatures, the electrical efficiency of these collectors is lower. Therefore, the choice between the glazed and unglazed collectors highly depends on the priority of thermal or electrical energy production.

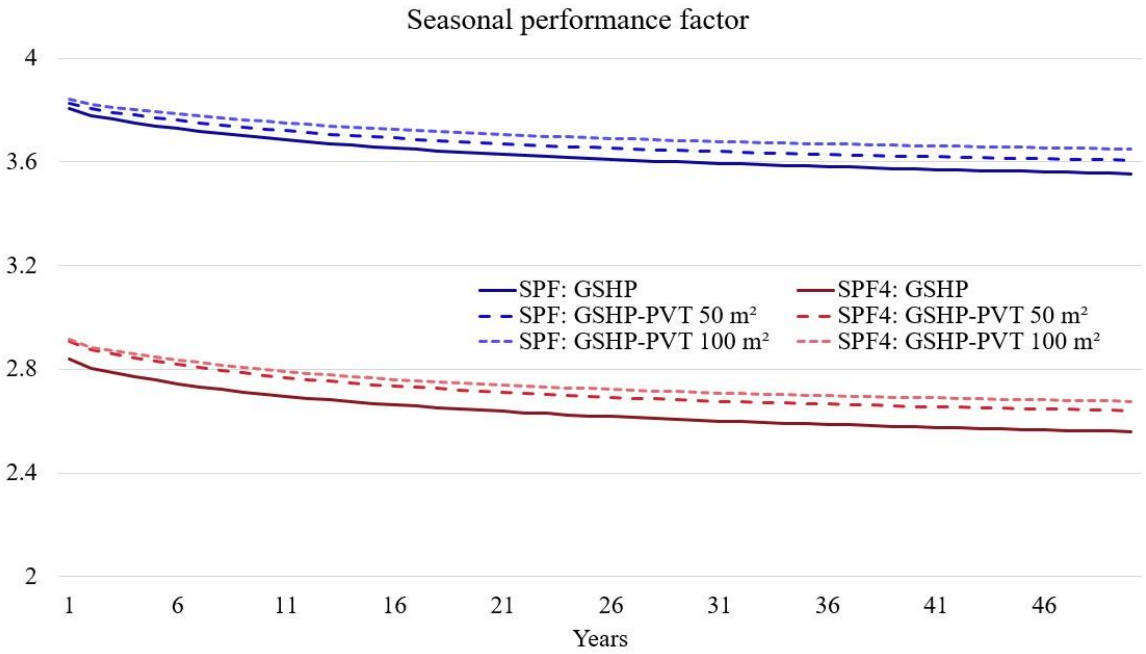

Fig. 6. Yearly variation of SPF and SPF_4 of GSHP and GSHP-PVT systems with 50 m^2 and 100 m^2 collector area.

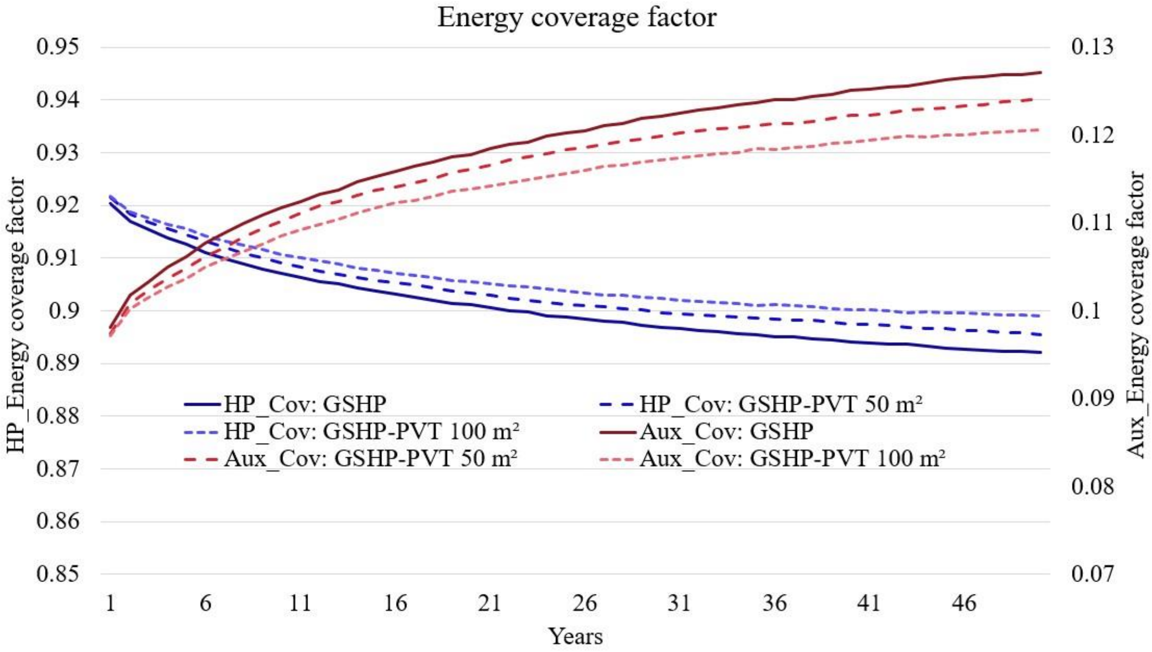

Fig. 7. Yearly variation of HP and auxiliary system energy coverage of GSHP and GSHP-PVT systems with 50 m^2 and 100 m^2 collector area.

In order to investigate the effect of using each system layout on the ground heat extraction, 5 different cases are compared: standard GSHP, GSHP with glazed or unglazed PVT collectors with downstream or upstream layouts. Figure 8 shows the monthly variation of heat extraction/rejection from/to the BH field in different cases with 12 BH and 100 m^2 PVT collectors. According to this chart, the net amount of heat extraction in upstream layout from the BH is insignificantly lower than that of downstream configuration. The reason for this difference can be explained by the difference between the inlet temperature to the BH. In upstream layout, the outlet flow from the evaporator side of the HP flows into the plate heat exchanger and extracts energy from PVT loop and then enters the BH, while in downstream flow, the outlet from the HP directly flows into the BH without being recharged by PVT loop. Also, it can be observed that using glazed PVT collectors, more thermal energy can be injected into the ground compared to the cases with unglazed PVT, which results in having lower net energy extraction from the BH during the year. Therefore, it can be concluded that the upstream layout using glazed PVT collectors has lower BH temperature reduction compared to other cases.

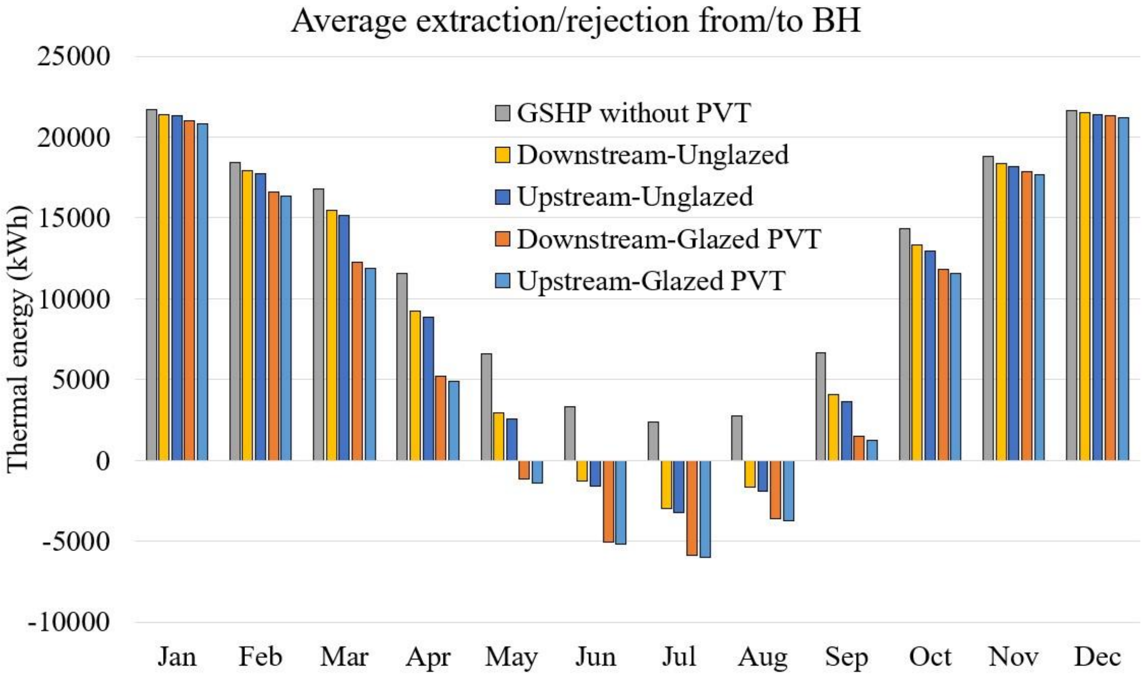

Fig. 8. Monthly variation of heat extraction/rejection from/to BH in different cases with 12 BH and 100 m^2 PVT collectors.

Table 1 shows the SPF and SPF$_4$ of the standard GSHP, GSHP with glazed and unglazed PVT for both downstream and upstream layouts. In this table the reduction in system performance after 50 years of operation can be observed. According to the table, approximately 6.6% reduction in SPF of GSHP system without PVT collectors can be seen from the first to the last year of operation. As explained earlier, this reduction is due to the reduction in the BH temperature. In case of using PVT collectors, since a part of the extracted heat from the BH can be regenerated, less reduction in SPF and SPF$_4$ can be seen. For instance, the downstream case with 100 m^2 of glazed PVT shows only 4.1% reduction SPF after 50 years.

Also, it can be concluded that the percentage of the reduction in SPF and SPF$_4$ in cases of using upstream layout is slightly lower than that of downstream, since in this configuration, the amount of net heat extraction from the BHs is slightly lower than that of downstream. However, the system performance in downstream cases is higher than that of upstream layout. The reason for this statement is the higher inlet temperature of the flow which enters the evaporator side of the HP. As clearly shown in figure 1, in downstream flow, the outlet flow from the BH first enters the plate heat exchanger and absorbs the thermal energy from PVT loop and then, flows into the HP, while in upstream flow, the outlet flow from the BH directly enters the HP.

Also, it can be seen that the system performance in cases with glazed PVT collectors is slightly higher than the cases with unglazed PVT. As explained earlier, glazed PVT collectors have better thermal efficiency because of a layer of air gap between the cover glass and PV cell, which acts as a layer of insulation. Therefore, it can be expressed that for this system, the downstream layout using the glazed PVT collectors can show better performance, in terms of thermal efficiency, compared to the other investigated cases.

Another interesting fact from this table is that by using PVT collectors, a smaller BH field can be used while achieving the same performance than a standard GSHP (without PVT). For instance, the SPF of the standard GSHP system with 12 BHs in the first and last year of operation is 3.8 and 3.55, respectively, which is close to that of downstream case with 50 m^2 glazed PVT collectors with 10 BHs, which varies from 3.8 to 3.58 after 50 years. By comparing these two cases, it can be concluded that using PVT collectors can compensate the reduction in BH temperature and it can also help the system to have smaller BH fields for a same thermal performance (here a reduction of 16%).

Table 1. SPF and SPF_4 reduction of different cases after 50 years of operation

Case	PVT area [m^2]	Number of BHs	Year	SPF	SPF_4
GSHP	-	12	1	3.8	2.84
			50	3.55	2.56
GSHP	-	10	1	3.75	2.77
			50	3.49	2.49
GSHP-Unglazed PVT Downstream	50	12	1	3.82	2.91
			50	3.6	2.64
GSHP-Unglazed PVT Downstream	50	10	1	3.78	2.84
			50	3.54	2.57
GSHP-Unglazed PVT Downstream	100	12	1	3.84	2.91
			50	3.65	2.68
GSHP-Unglazed PVT Downstream	100	10	1	3.79	2.85
			50	3.59	2.61
GSHP-Unglazed PVT Upstream	50	12	1	3.82	2.9
			50	3.6	2.64
GSHP-Unglazed PVT Upstream	50	10	1	3.77	2.84
			50	3.54	2.57
GSHP-Unglazed PVT Upstream	100	12	1	3.83	2.9
			50	3.64	2.67
GSHP-Unglazed PVT Upstream	100	10	1	3.78	2.84
			50	3.58	2.61
GSHP-Glazed PVT Downstream	50	12	1	3.85	2.92
			50	3.64	2.67
GSHP-Glazed PVT Downstream	50	10	1	3.8	2.86
			50	3.58	2.6
GSHP-Glazed PVT Downstream	100	12	1	3.89	2.95
			50	3.73	2.75
GSHP-Glazed PVT Downstream	100	10	1	3.84	2.88
			50	3.67	2.68
GSHP-Glazed PVT Upstream	50	12	1	3.83	2.91
			50	2.62	2.65
GSHP-Glazed PVT Upstream	50	10	1	3.78	2.84
			50	3.56	2.59
GSHP-Glazed PVT Upstream	100	12	1	3.85	2.92
			50	3.7	2.72
GSHP-Glazed PVT Upstream	100	10	1	3.8	2.86
			50	3.64	2.66

Another parameter which has been studied, is the electricity production using the PVT collectors. Figure 9 depicts the monthly electricity production of 100 m^2 PVT collectors and the annual solar production using glazed and unglazed collectors are 12.6 MWh and 13.5 MWh, respectively. In conclusion, while the glazed PVT collectors improve the thermal performance compared to unglazed PVT, they reduce the electricity production. In future work, this balance between electricity used by the GSHP and the electricity generated by the PVT should be investigated.

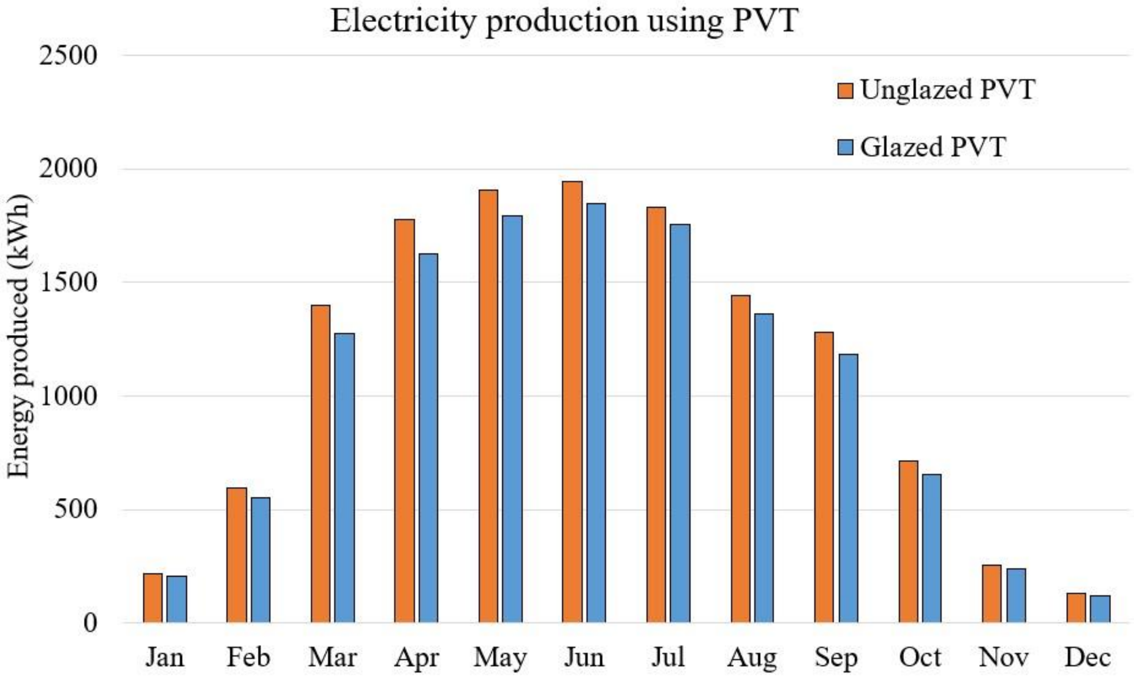

Fig .9. Monthly variation of energy produced by 100 m^2 PVT collectors.

4. Conclusions and future works

In this study, the long-term performance analysis of a combined system of GSHP-PVT with different layouts, downstream and upstream, and glazed and unglazed PVT collectors over the period of 50 years is investigated. The results of this study confirm that using PVT collectors can significantly impact the amount of heat extracted from the BH fields. Also, it can be concluded that the upstream flow results in lower temperature reduction in the BH filed compared to downstream flow. Furthermore, the results show that the downstream flow with glazed PVT collectors can exhibit better thermal performance in comparison with the other investigated cases.

One of the most interesting results obtained by this study is using PVT collectors in GSHP systems to reduce the size of the BH fields. For instance, the SPF of the standard GSHP system with 12 BHs over the period of 50 years is approximately similar to that of the downstream case with 50 m^2 glazed PVT collectors with 10 BHs. As the future works, it is worth studying the techno-economic performance of these systems to evaluate the gains in life cycle costs, including investment costs. In other words, it should be clarified that how much gain, in terms of investment costs, can be achieved by adding PVT collectors to the system and reducing the BH size.

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