Coupling PV/T Collectors with a Ground-Source Heat Pump System in a Double U-tube Borehole

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ABSTRACT

This paper examines the possibility of using a double U-tube borehole as a heat exchanger between two independent circuits. One U-tube is linked to a 10 m² unglazed photovoltaic-thermal (PV/T) collector and the other to a water-to-water heat pump. The objective of the paper is to quantify the benefits of this proposed system on the seasonal performance factors (SPF) of a ground-source heat pump system used for space heating and domestic water heating of a house located in a northern climate. Results show that the proposed system provides 7.7% more electricity than an uncoupled system because the PV/T panels are cooled by the heat transfer fluid from the borehole. However, 81 kWh per year of energy is required to pump this fluid. The heat transferred from the PV/T panels to the borehole increases the average inlet temperature to the heat pump by about 1.5°C which translates into better coefficients of performance (COP) for the heat pump. However, the COP is not the best metric and SPFs, which include pumping energy, represent a better performance indicator. It is shown that the global value of the SPF increases from 2.82 to 2.88 when the reference system and the proposed system are compared.

INTRODUCTION

In this article, a double U-tube borehole is used to couple unglazed photovoltaic-thermal (PV/T) collectors and a ground-source heat pump (GSHP) system. The double U-tube acts as a heat exchanger between two independent circuits: one U-tube is linked to the PV/T collectors and the other to the heat pump. This arrangement provides two main advantages. First, the PV/T collectors are cooled which increases the PV cells efficiency and electricity production. Secondly, the ground is thermally recharged which increases the inlet fluid temperature to the heat pump and consequently the coefficient of performance (COP) in heating. The objective of this paper is to quantify, using multi-year simulations, the energy benefits of this proposed configuration for a residential application where a ground-source heat pump system provides space heating and domestic hot water heating (DHW) for a house in a northern climate.

LITERATURE REVIEW

For ground-source heat pump systems used in cold climates, unbalanced heating/cooling loads result in a reduction of the ground temperature surrounding boreholes thereby decreasing the heat pump performance. One solution to this problem is to use thermal solar collectors to recharge the ground. Bakker et al. (2005) examined the combination of PV/T collectors with a single U-tube borehole combined to a ground-coupled heat pump. They report that a 25 m² PV/T panel produces as much energy as a 26 m² thermal solar collector and a 7 m² PV panel combined. Furthermore, they observe that heat injection into the ground keeps the ground temperature constant. Trillat-Berdal

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(2006) showed that by using unglazed solar collectors to recharge the borehole, the COP of the heat pump is reduced by only 7% over a period of 20 years instead of 9% for a conventional GSHP. Pahud and Lachal (2004) analyzed a system providing space heating and domestic hot water to a single family house in Switzerland. Thermal solar collectors are used to produce DHW and excess solar energy is injected into a borehole. Their results show that the solar panels provide 20% of the heat extracted from the ground during one year, slightly increasing the COP of the heat pump. In addition, coupling the solar panels to the ground prevents solar collectors from overheating. However, the system requires an additional circulating pump, the electric consumption of which cancels out the energy saved by heat injection.

Eslami-Nejad and Bernier (2011) and Eslami-Nejad et al. (2009) coupled thermal solar collectors to a GSHP system using a four-pipe borehole with two independent U-tube circuits. The results of these studies indicate that the amount of energy extracted from the ground can be reduced by up to 67% using such a system. However, the heat pump energy consumption is only slightly reduced.

Kjellsson et al. (2005) concluded that when thermal solar collectors are used in combination with a ground-source heat pump, it is best to use the thermal solar collectors for DHW heating in the summer and borehole recharging in the winter. Yang et al. (2015) examined experimentally the various possibilities of combining thermal solar collectors, a storage tank, a heat pump, and boreholes. The highest COP was achieved when the borehole outlet was linked to the solar storage tank and the storage tank outlet to the evaporator inlet and then back to the boreholes. However, pumping energy was not considered in their analysis. Man et al. (2011) analyzed a PV/T system used in nocturnal cooling mode. They showed that the cooling provided by the PV/T at night was not sufficient to reach the desired temperature. However, the cost of cooling was reduced by about 10% compared to a traditional system.

Bertram et al. (2012) concluded that the use of unglazed PV/T collectors as additional heat source in heat pump systems with borehole heat exchangers increased the PV/T yield by about 4%. The improvement in the value of the seasonal performance factor is 0.36 in the first year and 0.41 for the 20th year of operation.

PROPOSED CONFIGURATION

The proposed configuration is presented on Figure 1. It is similar to the configuration used in a companion paper (Hache et al. 2016) except that a PV/T loop and a second U-tube in the borehole have been added to the system. A 10 kW (3 tons) water-to-water ground source heat pump is used to supply space heating and domestic hot water to a well-insulated 220 m² (2368 ft²) house. A three-way valve is used to divert the flow from one tank to the other with priority given to the buffer tank for space heating.

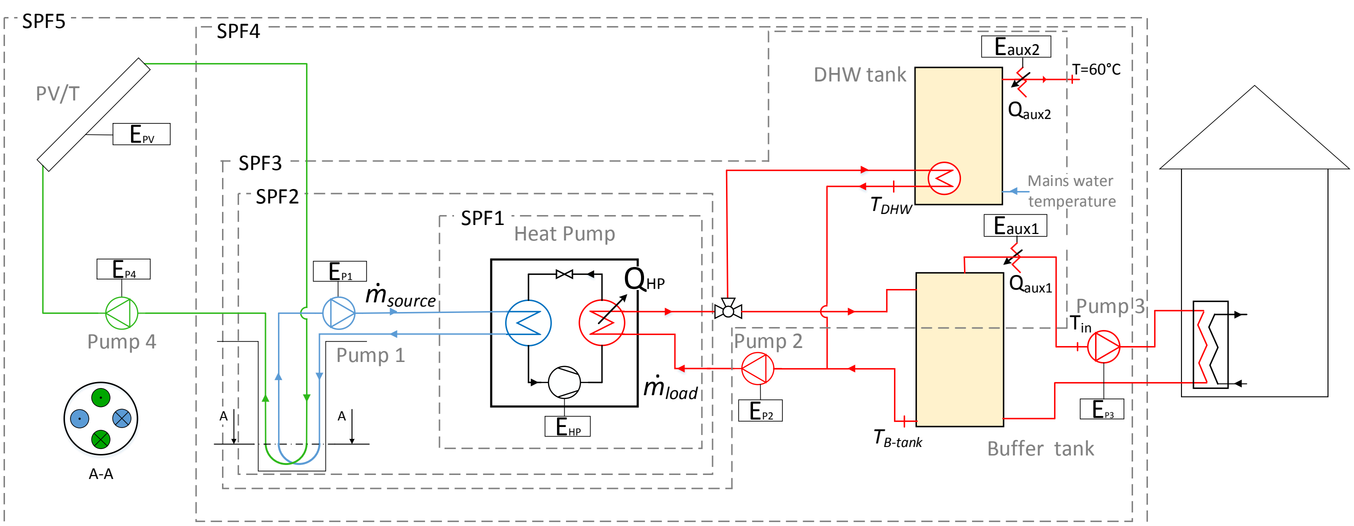


Figure 1 Schematic diagram of the proposed system with a definition of the SPF boundaries.

When the return temperature from the DHW tank, T_{DHW}, falls below 45°C (113°F) then the heat pump is started along with pumps P1 and P2. Typically, the top temperature in the DHW tank is around 55°C (131°F) and a small amount of auxiliary heat is required to reach the desired temperature of 60°C (140°F). When the air temperature in the house drops below 21°C (69.8°F), pump P3 is activated. If the air temperature continues to drop then an auxiliary heater is energized at 20°C (68°F) to supplement the heat from the buffer tank. If the temperature in the bottom of the buffer tank, $T_{B\text{-}tank}$, drops below 30°C (86°F) then the heat pump as well as pumps P1 and P2 are activated. The resulting top temperature in the buffer tank is around 40°C (104°F) which is typically sufficient to provide about 85% of the annual space heating requirements; the rest is given by the auxiliary heater. Both the source and load flow rates are set to 0.28 L/s (4.5 gpm). Characteristics of the main components and operating conditions, including the assumed pressure drops in the various parts of the system, are detailed in Table 1.

The GSHP is linked to one of the U-tube of the geothermal borehole. The other U-tube is linked to unglazed PV/T collectors. Both circuits are independent. Four modes of operation are possible: i) Both circuits operate simultaneously and the borehole acts as a heat exchanger between the two circuits; ii) the thermal output of the PV/T is insufficient to recharge the ground and the heat pump is not operating so both circuits are inactive; iii) only the heat pump loop operates in which case the borehole takes its normal role of collecting heat from the ground; iv) only the PV/T is in operation to thermally recharge the borehole.

The studied building is a typical Canadian single-family house located in Montreal, Quebec. Peak demand for space heating is approximately 8.7 kW (29.7 kBTU/hr) and the annual house space heating requirement is ≈ 20800 kWh (≈ 71 MBTU). The daily domestic hot water consumption is 210 liters (55.5 gallons). The water draw profile is presented in the companion paper (Hache et al., 2016). On an annual basis, approximately 5000 kWh are required to heat the water from the water mains temperature to 60°C (140°F).

The working fluid circulating on the heat pump side of the borehole is propylene glycol (25%) in accordance to the system presented in the companion paper. On the PV/T side, methanol with a concentration of 40% is used. Such a high concentration is required due to the exposure of the solar panels to extreme cold weather (≈ -30°C). The use of propylene glycol on the collector side would have led to laminar flow in the U-tube for certain conditions.

Table 1. Characteristics of the Main Components and Operating Conditions

Parameter	Value	Unit
$\dot{m}_{source}, \dot{m}_{load}$	1034 (2280), 1008 (2222)	kg/h (lb/h)
$\dot{m}_{PV/T}$	600 (1320)	kg/h (lb/h)
P1 (η=15%) Pressure drop	72 (236)	kPa (ft)
P2 (η=10%) Pressure drop	16 (53)	kPa (ft)
P3 (η=15%) Pressure drop	50 (164)	kPa (ft)
P4 (η=10%) Pressure drop	25 (82)	kPa (ft)
Volume of DHW and buffer tanks	0.35 (93), 2 (528)	m^3 (gallons)
PV/T Area	10 (108)	m^2 (ft^2)

METHODOLOGY

The energy performance of the system is assessed with multi-year simulations using TRNSYS (Klein et al. 2010) as the simulation engine. A comparison is made between the proposed system and a reference system. The reference system is identical to the proposed system except that the PV/T collectors are independent of the rest of the system and the borehole contains only one U-tube linked to the GSHP. Moreover, there is no fluid circulating in the PV/T collectors of the reference system, hence they act as regular PV collectors.

Models

Standard TRNSYS types are used in the simulation including TYPE741 for calculating pumping energy and TYPE534 for both tanks. The ground source heat pump is modeled using TYPE927 which determines the performance of the heat pump (capacity and power input) by interpolating in a performance map. Figure 2 gives the capacity and COP of the GSHP used here as a function of the entering water temperature on the source side for a fixed value of the load side temperature of 35°C (95°F). Both the capacity and COP increase with an increase of the entering water temperature on the source side.

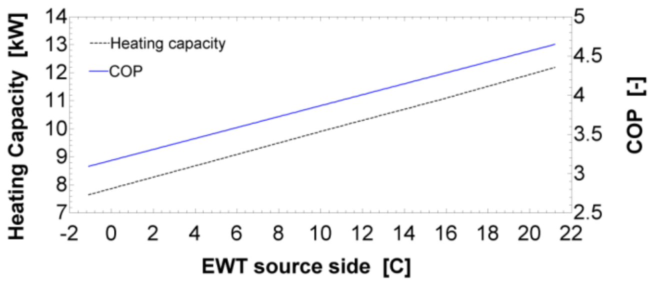


Figure 2 Heat pump performances as a function of the fluid temperature on the source side.

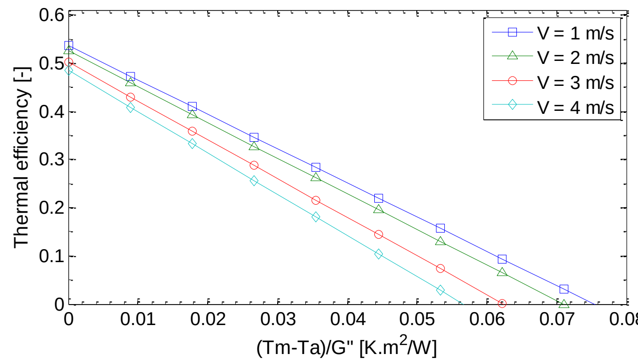
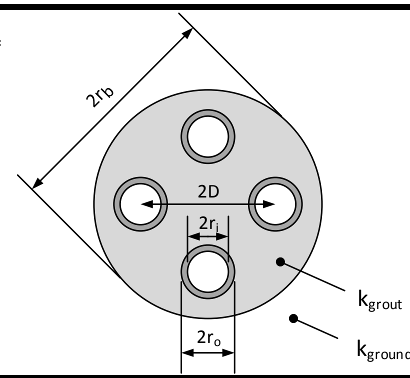


Figure 3 Thermal efficiency of the PV/T collectors for different wind speeds.

The four-pipe ground heat exchanger model developed by Godefroy (2014) is used here. It is based on the TRC (Thermal Resistance Capacity) approach, thus fluid and grout thermal capacities are accounted for. Furthermore, it can model two independent circuits such as the ones used here. The borehole characteristics are given in Table 2.

Table 2. Borehole Parameters

Parameter	Value	Unit
Borehole length	140 (460)	m (ft)
Buried depth	1 (3.28)	m (ft)
Borehole diameter ($2r_b$)	0.15 (6)	m (in)
Pipe outer diameter ($2r_o$)	0.032 (1.25)	m (in)
Pipe inner diameter ($2r_i$)	0.026 (1.0)	m (in)
Shank spacing (D)	0.04 (1.57)	m (in)
Ground thermal conductivity (k_{ground})	2.22 (1.27)	W/m.K (Btu/h.ft.°F)
Grout thermal conductivity (k_{grout})	0.83 (0.48)	W/m.K (Btu/h.ft.°F)



In PV/T collectors, PV cells are mounted on top of an absorber plate with pipes welded to it. Fluid circulates through the pipes thereby collecting thermal energy and cooling the PV cells. In the proposed system, PV/T collectors are simulated using TRNSYS TYPE560 (TESS, 2004) with its default values except for the PV cells efficiency at reference conditions which is set to 15% and the flow rate which is equal to 60 kg/h (132 lb/h). The total surface of the collectors is equal to 10 m² (108 ft²). The slope of the collectors with respect to the horizontal is 60° to maximize the energy gain during the winter. The electrical and thermal efficiencies are calculated according to the EN 12975-2 standard (2006). Since the collectors are unglazed, the available solar energy per unit surface corresponds to the net irradiance G" (incident solar radiation reduced by longwave radiation). Unglazed solar collectors are relatively sensitive to the wind velocity because the convective heat loss coefficient has a relatively important effect on the thermal efficiency. In the present case, the top loss coefficient is calculated at each time step according to Equation 1, proposed by Duffie and Beckman (2013):

$$h_{top} = \max[5, \frac{8.6V^{0.6}}{L^{0.4}}] \qquad (1)$$

where V is the wind velocity taken from the weather file and L is the cubic root of the house volume, assumed equal to 8 m. The resulting thermal efficiency of the PV/T collector is shown on Figure 3. These performances are similar to a commercially-available unglazed PV/T collector (Solimpeks, 2015).

Pump P4 is activated when the difference between the PV/T outlet temperature and the average borehole wall temperature is higher than 10°C (18°F). It is turned off when this same temperature difference becomes lower than 3°C (5.4°F).

Seasonal Performance Factors

The efficiency of both the reference and proposed systems is evaluated using the concept of seasonal performance factors (SPF) which accounts for all the energy exchanges in the system within certain boundaries. These boundaries are identified in Figure 1. The four basic values of the SPF (SPF1 to SPF4) established by Nordman and Zottl (2011) are:

$$SPF1 = \frac{Q_{HP}}{E_{HP}} \ , \quad SPF2 = \frac{Q_{HP}}{E_{HP} + E_{P1}} \ , \quad SPF3 = \frac{Q_{HP} + Q_{aux1} + Q_{aux2}}{E_{HP} + E_{P1} + E_{aux1} + E_{aux2}} \ , \quad SPF4 = \frac{Q_{HP} + Q_{aux1} + Q_{aux2}}{E_{HP} + E_{P1} + E_{P2} + E_{P3} + E_{aux1} + E_{aux2}} \quad (2a, b, c, d)$$

Values of Q represent annual amounts of heat introduced into the system either from the heat pump, Q_{HP}, or from the two auxiliary heating elements, Q_{aux1} and Q_{aux2}. Values of E represent annual amounts of energy supplied to each component: E_{HP} for the heat pump, E_{P1}, E_{P2}, E_{P3} for the various circulating pumps, and E_{aux1} and E_{aux2} for the two electric heating elements. An additional SPF, denoted as SPF5, is proposed here to account for the PV/T loop:

$$SPF5 = \frac{Q_{HP} + Q_{aux1} + Q_{aux2}}{E_{HP} + E_{P1} + E_{P2} + E_{P3} + E_{aux1} + E_{aux2} + (E_{P4} - E_{PV})} \quad (3)$$

where the term in parenthesis in the denominator is the difference between the annual energy consumption of pump P4 and the annual electricity production of the PV/T collector. For the reference system $E_{P4} = 0$. This definition is valid only if the total electricity consumption is higher than the electricity production from the PV/T.

RESULTS AND DISCUSSION

Both the reference and proposed systems are simulated for ten years with a 6 minute time step. The influence of the heat injection from the PV/T collectors on the heat pump entering temperature is shown on Figure 4. The average inlet temperatures over the 10 year period for the reference and proposed systems are 3.4 and 5.2°C (38.0 and 41.3°F), respectively. However, the difference between these two temperatures is not constant during the year. During the heating season, the inlet temperature is ≈ 0.5°C (≈ 0.9°F) higher with the proposed system when compared to the reference system. However, from May to the end of September, it is ≈2.7°C (≈4.9°F) higher on average. The minimum inlet temperatures for the proposed and reference systems are -3.6°C (25.5°F) and -4.3°C (24.3°F), respectively. Thus, heat injection from the PV/T limits the long-term ground temperature drop, albeit by a small amount.

As presented on Figure 5a, the amount of energy extracted from the ground during the first year is reduced by 29% from 14521 kWh (49.5 MBTU) for the reference system to 10339 kWh (35.3 MBTU) with the PV/T system. This is the result of heat exchanged between the two U-tubes when the PV/T loop is operating which reduces the heat requirements from the ground. The thermal energy from the solar panels reduces the energy extracted during the heating season by 11% on average. Furthermore, due to the relatively low heating load and the high solar energy availability in the summer, more energy is injected into the ground than is extracted. This is also reflected in the heat pump inlet temperature which reaches a maximum of 12°C (53.6°F), a value higher than the undisturbed ground temperature (10°C (50°F)).

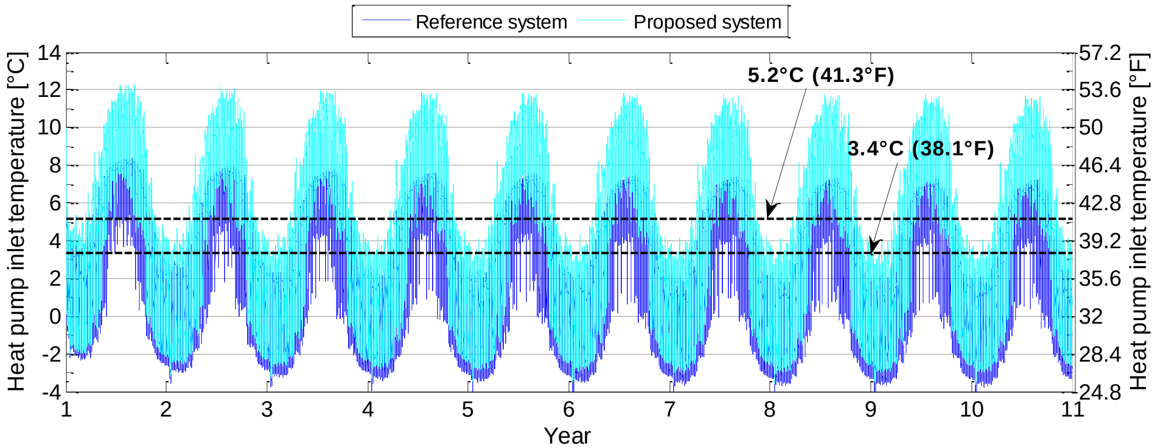


Figure 4 Heat pump inlet temperature on the source side during 10 years operation of the system.

As expected, the circulation of the fluid in the PV/T collectors improves the electricity production, especially during the summer (see Figure 5b). The PV cells reach a maximum temperature of 40°C (104°F) with the proposed system and 70°C (158°F) for the reference system. The annual energy produced by the PV/T collectors is equal to 1562 kWh for the proposed system which is 7.7% higher than the 1450 kWh produced by the reference system.

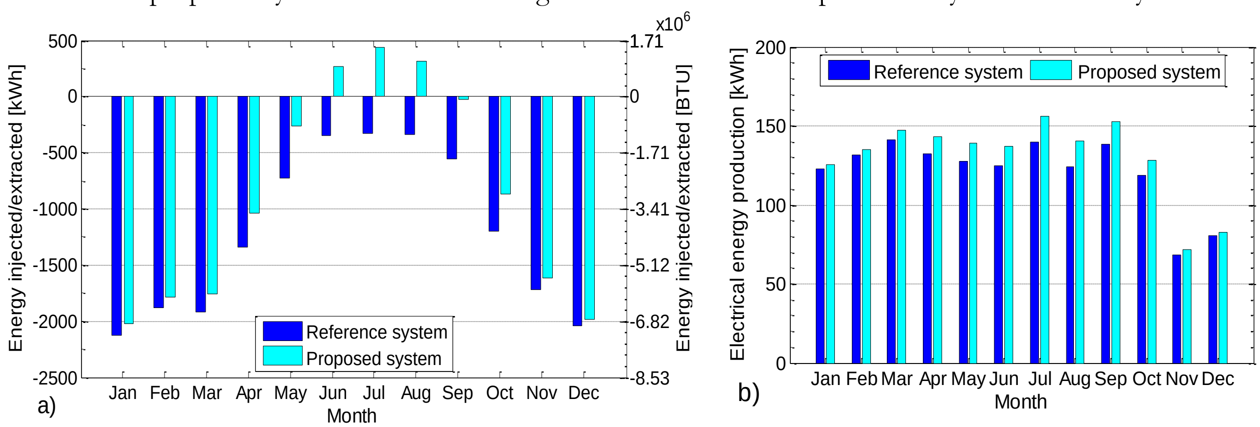


Figure 5 (a) Energy injected/extracted from the ground and (b) PV cells electrical energy production for the first year of operation.

As shown on Figure 6a, the increase of the temperature entering the heat pump results in an improvement of the overall system efficiency: SPF5 changes from 2.82 to 2.88 for the first year, and from 2.73 to 2.81 for the tenth year of operation. SPF1 to SPF5 increase by 1.7% and 2.6% on average for the first and tenth year, respectively, in accordance to the evolution of the heat pump inlet temperature over the years. It is worth mentioning that the presence of PV cells improves the SPF: SPF5 is about 18% higher than SPF4 for both systems.

The improvement of the SPFs implies a reduction of the energy consumption. The first year annual energy consumption for space heating and DHW heating (with electricity production accounted for) is decreased by 1.9%: the reference and proposed system use 8215 kWh and 8060 kWh, respectively. More details on the energy consumption during the first year are presented in Table 3. The benefits of heat injection into the borehole is more apparent with time: for the tenth year, the energy consumption of the system is reduced by 2.7% with an energy consumption of 8497 kWh (29.0 MBTU) instead of 8269 kWh (28.2 MBTU).

Table 3. Annual Energy Consumption/Production For the First Year [kWh]

System	Q_{HP}	E_{HP}	E_{AUX1}	E_{AUX2}	E_{P1}	E_{P2}	E_{P3}	E_{P4}	E_{PV}
Reference	20523	6145	2494	145	337	112	432	-	-1450
Proposed	20578	6046	2489	132	331	110	432	81	-1562

Figure 6b presents the results of a parametric study carried out on the following parameters: the shank spacing, the ground and the fill conductivity (D, k_{ground} and k_{grout} in Table 2, respectively). Each of these parameters has been reduced and increased below and above the values listed in Table 2. For example, a reduction of the shank spacing down to 65% of the value listed in Table 2 reduces the value of SPF5 by about 1.5%. The results presented in Figure 6b tend to indicate that the performance of the proposed system is not very sensitive to variations of D, k_{ground} and k_{grout} with changes of 2 to 3 % in the value of SPF5.

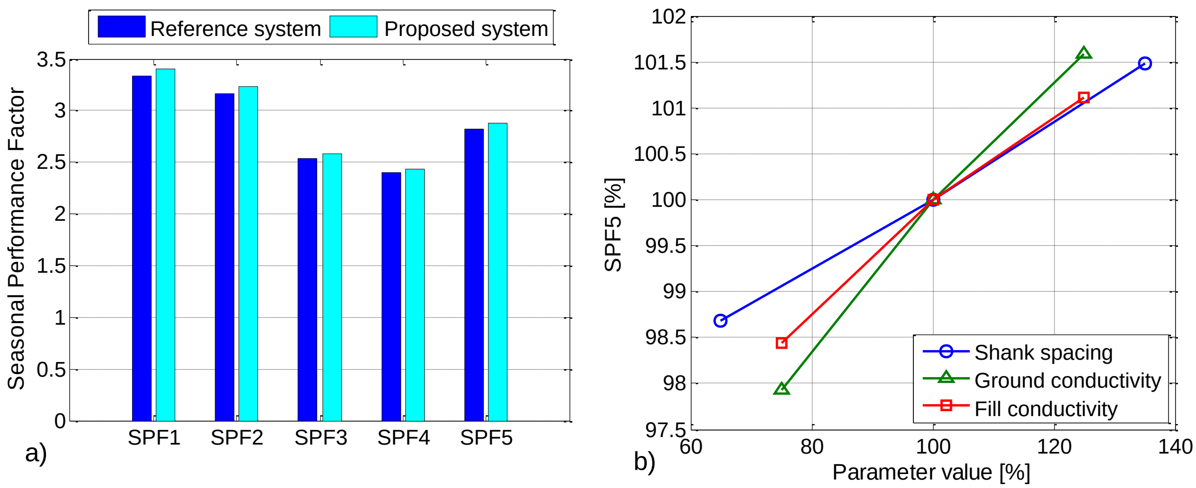


Figure 6 (a) Annual SPFs and (b) influence of the borehole parameters on the SPF5 of the proposed system.

The relatively small increase in the value of SPF5 between the reference and proposed systems observed in Figure 6a is due to several factors. First, exposure of the solar panels to high wind speeds and extreme cold temperatures during the heating season means that the working fluid rarely reaches the required temperature for the injection of heat into the borehole. Moreover, since there is only one borehole, the heat injected into the ground during the summer diffuses to the surroundings which reduces its availability for the next winter. These two effects can be indirectly observed using the results shown in Table 4 which presents the average SPFs over the summer (from the beginning of May to the end of September) and over the heating season (from October to the end of April) for both systems. The performances of the proposed system are 16.8% higher on average during the summer. However, during the heating season they are only 2.5% higher. Given that the heating season represents the most important load, improving the efficiency during the summer has negligible repercussions on the overall efficiency of the system.

Table 4. SPF1 and SPF5 for the Summer and Heating Seasons

	SPF1		SPF5	
	Reference system	**Proposed system**	**Reference system**	**Proposed system**
Summer	3.02	3.15	7.33	8.56
Heating season	3.40	3.46	2.84	2.91

CONCLUSION

The system presented in this study consists of PV/T collectors coupled to a GSHP using a double U-tube borehole with two independent circuits. The system is used to provide space heating and DHW for a typical residence located in a cold climate. The energy performances of this proposed system as well as the one of a reference system with no coupling of the PV/T to the ground are assessed using multi-year simulations in TRNSYS.

The traditional definition of the seasonal performance factors has been extended to include the electricity production of the collectors and the extra pumping energy. The results show that with 10 m² of PV/T, the SPF is increased from 2.82 to 2.88 compared to the reference system. The annual energy produced by the PV/T collectors is equal to 1562 kWh for the proposed system which is 7.7% higher than the 1450 kWh produced by the reference system. The amount of energy extracted from the ground by the heat pump in one year is reduced by 29% with the proposed configuration.

The unglazed PV/T collectors do not have a significant influence on the performance of the system during the heating season due to the cold weather which prevents the working fluid from heating up above the borehole temperature. Moreover, part of the heat injected in the ground during the summer diffuses to the surroundings reducing the availability of the injected heat to be used during the next winter.

It is believed that the performance of the proposed system could be improved using glazed PV/T collectors which could provide more heat into the borehole in winter. Furthermore, it might be preferable to use multiple shorter boreholes in series so as to form a radially stratified thermal storage to increase the storage of heat produced by the PV/T in the summer.

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