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# Solar PVT-assisted regeneration of boreholes with thermal imbalance in GSHP systems: a techno-economic analysis

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**Abstract**

Unbalanced ground source heat pump (GSHP) systems in cold climates can experience ground cooling and reduced performance over the long-term. This study evaluates whether unglazed PV/thermal hybrid collectors (PVT) can restore performance when added after ten years of GSHP operation. A single-family house is simulated for 20 years, with four PVT designs introduced from year eleven onward to assess effects on seasonal performance factor (SPF), auxiliary-heater use, borehole temperature, thermal balance, and life-cycle cost. All PVT configurations produce an immediate $SPF_{4+}$ increase of 0.6 % to 0.9 % and stabilize 1.3–1.6 % above the GSHP-only case by year 20. Borehole temperatures, which decline from 7.0 °C to 5.6 °C during the first decade, recover to 6.4–6.6 °C, and 40 % of extracted heat is reinjected over the PVT period. However, total life-cycle costs rise by 31–54 % due to high capital costs. PVT therefore offers limited technical benefits and remains economically challenging under current cost conditions for a fully sized borehole field. Future work should examine older systems and heat-pump replacement scenarios.

*Keywords: Borehole regeneration; Thermal imbalance; Ground cooling; Seasonal performance factor; Auxiliary heating; Techno-economic analysis;*

## 1. Introduction

In countries with cold climates such as Sweden, ground source heat pumps (GSHPs) play a central role in keeping homes warm. They are the most energy-efficient heating technology and constitute a large share of the installed heat pump stock. According to Swedish Energy Statistics for one- and two-dwelling buildings, 36 % of houses with heat pumps rely solely on GSHP for space heating (SH) and domestic hot water (DHW), while an additional 10 % combine heat pumps with other systems [1]. As shown in Figure 1, GSHPs are the single most common heat pump type in this segment, with around 300,000 homes already using GSHPs in 2009 and over 400,000 today. This also means that a large portion of the existing GSHP stock has been operating for more than a decade, many for 15-20 years, typically without any form of active borehole regeneration, and a substantial share of these installations have either already replaced the heat pump unit or are now approaching the replacement stage.

Long-term field measurements by Rybach and Eugster [2] on a 105 m borehole heat exchanger in Switzerland demonstrated that continuous heating-only operation produces a sustained thermal imbalance in the surrounding ground. Over the first decade of operation, temperatures within several metres of the borehole declined steadily and eventually stabilized about 1–2 K below the undisturbed ground temperature. Repeated vertical temperature profiling over twelve years revealed the formation of a cooled zone extending along the full borehole depth, effectively creating a persistent thermal plume. This cooling established steep radial temperature gradients that drove significant heat inflow from the surrounding ground toward the borehole, reaching peak fluxes of roughly 3 W/m², more than an order of magnitude above the natural geothermal flux of ~0.08–0.10 W/m². Numerical extrapolation of the field data to a 30-year period reproduced the same behaviour: an initial decade of rapid temperature decline followed by a gradual approach to quasi-steady conditions as radial heat inflow increasingly balances extraction. A subsequent 30-year recovery simulation indicated that once extraction stops, ground temperatures rebound quickly during the first few years and then recover asymptotically, with only small residual deviations after three decades. [3]

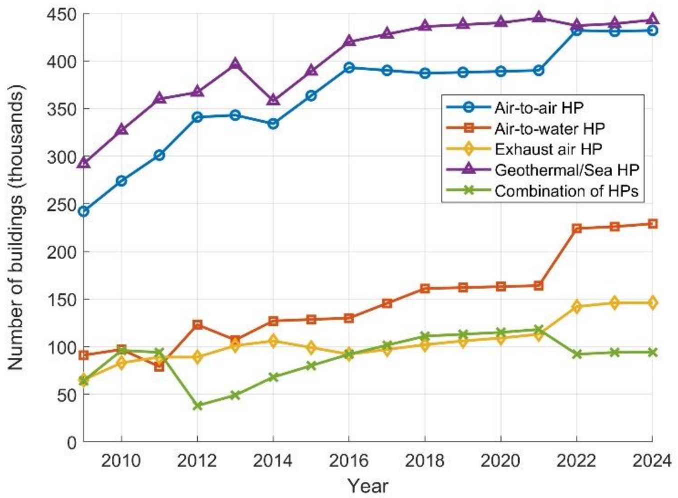


Figure 1. Number of heat pump installations in one and two-dwelling buildings by heat pump type from 2009 to 2024 [1].

In addition to the long-term thermal response in the abovementioned single-borehole measurements, the overall performance of GSHP systems is strongly shaped by the annual balance between heat extraction and heat injection. When the seasonal heating and cooling loads are not thermally balanced, the ground can experience a gradual net cooling or warming trend, which may degrade system efficiency over time and, in dense urban settings, alter the subsurface temperature field sufficiently to influence nearby installations through thermal interference [4]. The degree of imbalance is commonly quantified using the Thermal Imbalance Ratio (TIR), defined as the annual difference between extracted and injected heat divided by the larger of the two magnitudes; values approaching zero indicate a thermally neutral operating regime. Several site-specific factors, including soil thermal conductivity, moisture conditions, undisturbed ground temperature, grout thermal properties, and borehole spacing, affect how sensitive a system is to such imbalance [5]. As an alternative indicator, Liravi et al. [6] propose the Thermal Balance Ratio (TBR), which expresses the annual ratio of heat injected to heat extracted and enables classification of the borehole field as being in a deficit, surplus, or near-balanced state from year to year.

In many existing GSHP systems, the issue of thermal imbalance becomes most apparent at the time of heat pump replacement. Boreholes installed 15–20 years ago were typically sized for lower extraction rates, and installing a more efficient, variable speed heat pump increases the thermal load on an already depleted ground volume. The conventional approach is to drill additional boreholes, but this is costly, intrusive, and often limited by land availability. This raises a relevant question: can renewable energy sources regenerate the ground and restore system performance without the need for new wells?

Photovoltaic-thermal (PVT) collectors have emerged as a promising option for addressing long-term thermal imbalance in GSHP systems. PVT collectors generate both electricity and low-temperature heat in a single unit, and their low-temperature heat aligns with the temperature levels required by GSHP evaporators and borehole regeneration. Unlike glazed solar thermal collectors, unglazed PVT units operate efficiently at fluid temperatures below ambient and can capture convective heat from the surrounding air, making them particularly suitable for Nordic climates [7]–[9]. Prior modelling studies have shown that this low-temperature heat can raise evaporator inlet temperatures, reduce compressor lift, and inject energy into the ground to counteract long-term subsurface cooling [6], [10]. A cross-sectional diagram of an unglazed sheet and tube collector can be seen in Figure 2.

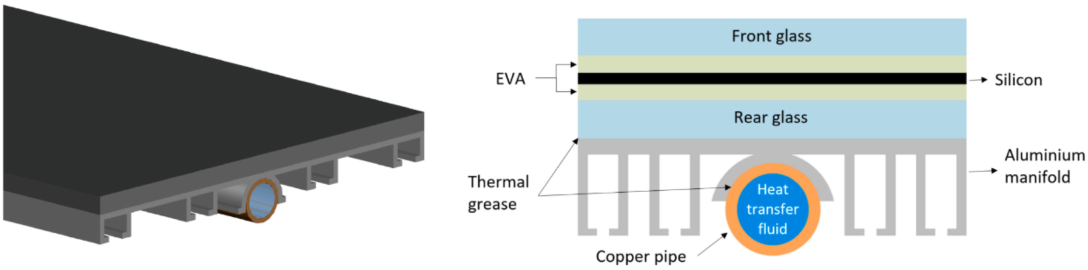


Figure 2. Cross-sectional diagram of an unglazed sheet and tube collector [21].

Sommerfeldt et al. [11] examined a multi-family house GSHP system operating with a reduced borehole field and introduced PVT in year 10 to counteract long-term thermal degradation. They showed that $SPF_{4+}$, which had declined from 2.9 in year 1 to 2.3 by year 10, could be restored to 2.8–2.9 using 48–144 unglazed PVT collectors, matching the improvement achieved by drilling an additional 2100 m of borehole. The PVT systems (€ 40–100 k) were cost-competitive with drilling (€63 k) while also providing electricity generation. Beyond this case, other numerical studies have shown that the influence of PVT is most pronounced when the borehole field is undersized or thermally depleted. A German case study reported a 13 % seasonal performance factor (SPF) increase in an undersized system, compared with only 6 % in a correctly dimensioned one [9]. Sommerfeldt and Madani [10] likewise showed that PVT integration has marginal impact in correctly sized GSHP systems but becomes significant when land availability constrains borehole length or when prior thermal depletion is present. Their results indicate that each 10 m² of PVT can reduce required borehole length by ~0.8 % and spacing by 0.5 m while maintaining SPF4+, reducing land requirements by up to 89 %. In a 50-year Nordic climate study, Liravi et al. [6] found that PVT could reduce long-term ground temperature decline by 33 % in large borehole fields and cut required borehole area by up to 95 %. PVT performance is also sensitive to collector design. Beltrán and Sommerfeldt [12] experimentally characterized four unglazed PVT concepts under low-temperature Nordic conditions and implemented the measured performance coefficients in a TRNSYS multifamily model. Although finned absorbers delivered 7.4–10 % higher specific thermal output, they increased total life-cycle cost (TLCC) by up to 5.2 % and improved SPF by only ~0.6 %, indicating that economic, not thermal, optimization governs collector selection for GSHP integration.

While previous studies have shown that PVT can mitigate long-term ground cooling in GSHP systems, such as the studies by Bertram et al. [9] and Sommerfeldt et al. [11], existing work has either primarily examined multi-family buildings, intentionally undersized borehole fields, single PVT designs or lack an economic analysis. To the best knowledge of the authors, no study to date has evaluated technically and economically a single-family house (SFH) with a conventionally sized borehole, that has cooled over ten years of typical heating-dominated operation and is approaching the replacement stage. Likewise, the literature has not compared different unglazed PVT designs in terms of their ability to recover SPF, reduce backup-heating demand, restore borehole thermal balance, and improve life-cycle cost in this context. This leaves an important gap in understanding how PVT performs when integrated after a decade of operation in a standard SFH GSHP installation, which is the situation faced by many existing systems in Sweden. The present work addresses this gap by examining a single-family house that has operated a GSHP for ten years without regeneration, reconstructing the borehole's thermal degradation over that period, and assessing the technical and economic implications of integrating different PVT collectors from year eleven onward.

## 2. Objective and Research Questions

The objective of this study is to evaluate how different unglazed PVT collectors influence the long-term technical and economic performance of a single-family house equipped with a ground-source heat pump that has been operating for ten years without borehole regeneration. The work aims to determine how late-stage PVT integration affects ground temperature development, seasonal performance factor, borehole thermal balance, and life-cycle costs, and to identify how collector design influences these outcomes. To meet this objective, the study addresses the following research questions:

RQ1. How does adding different unglazed PVT collectors after ten years of GSHP operation affect the system's thermal performance and efficiency?

RQ2. How does late-stage PVT integration influence long-term borehole behavior, particularly the thermal balance and outlet temperature development?

RQ3. Under the defined economic conditions, how does the integration of PVT collectors affect the life-cycle cost of the system compared with GSHP-only alternatives?

**3. Methodology**

The methodological framework is structured to evaluate the technical and economic impact of integrating four different unglazed PVT collector designs into a single-family house (SFH) equipped with a ground-source heat pump (GSHP) that has operated for 10 years without borehole regeneration. The GSHP-only period (years 1–10) is simulated first to produce the progressive borehole temperature decline and associated deterioration in seasonal performance. At the beginning of year 11, a 30 m² PVT array, implemented using one of four different PVT collector types: sheet and tube (S&T), box-channel polypropylene (BC-PP), finned tube (FT), and box-channel aluminum with 20 mm fins (BC-AL-20), is introduced. The system is then simulated for an additional decade (years 11–20) to assess the influence of delayed PVT integration on seasonal performance factor ($SPF_{4+}$), borehole thermal balance, temperature recovery and total life-cycle cost.

$SPF_{4+}$ is defined as the ratio between the total useful thermal energy delivered for space heating and domestic hot water and the total electricity consumption of the heating system, following the same system boundary and definition as in Sommerfeldt and Madani [10]. The electricity consumption includes the heat pump compressor, the source- and sink-side circulation pumps, all auxiliary pumps associated with the PVT loop, and any auxiliary heater operation. Electricity generated by the PV part of the PVT collectors is not subtracted from the SPF denominator.

The simulation model in TRNSYS 18 [13] is adapted from the validated multi-family house (MFH) model developed by Sommerfeldt and Madani [10] and later extended by Beltran et al. [14] to incorporate empirically derived thermal coefficients for multiple PVT designs. The weather data used in this study corresponds to a typical meteorological year for Stockholm, Sweden, taken from Meteonorm 7.2 [15] . The SFH representation includes a heated area of 140 m², a south-facing roof with a 20° tilt angle for collector installation, and annual energy demands obtained from the International Energy Agency Solar Heating and Cooling (IEA SHC) Task 44 / Annex 38 reference values [16]. Space-heating demand is set to 115 kWh/m²yr, electricity consumption to 33 kWh/m²yr, and domestic hot water (DHW) use to 21 kWh/m²yr. The heat pump model uses the same condenser–evaporator–frequency interpolator and PI-controlled compressor logic as the original MFH model, but scaled down to satisfy 98 % of SH and DHW needs of the SFH, resulting in a maximum condenser output of 8.15 $kW_{th}$. A simplified schematic of the system is shown in Figure 3.

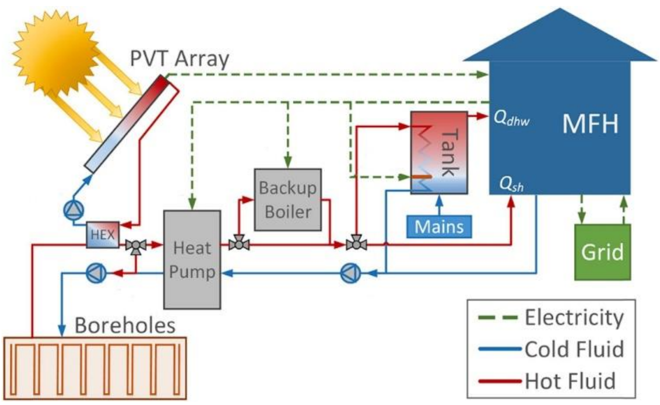


Figure 3. Schematic of the PVT + GSHP system [10].

Borehole depth is determined by simulating 20 years of GSHP-only operation using TRNSYS Type 557a. The results show that a 250 m depth is required to keep the average borehole outlet temperature at the end of the 20-year period, as well as the yearly minimum temperatures, above 0 °C, preventing ground freezing while limiting auxiliary-heater use to less than 2 %. This depth is therefore selected for all PVT scenarios. Although Type 557a is suitable for the present analysis, its underlying Duct Storage Model (DST) formulation, developed by Hellström [17], restricts the borefield to a uniform geometry and a single aggregated thermal history, making it less flexible for future studies involving irregular borehole layouts, phased field expansion, or boreholes with different operating ages. For this reason, The long-term borehole thermal response is computed using a Python model developed from Eskilson's g-functions [18], which is integrated into the TRNSYS environment through Type 3157. The model performs a convolution between past loads and the g-function response, solves for the outlet temperature using a fixed borehole resistance and a SciPy-based numerical solver, and is benchmarked against Type 557a by comparing extracted heat, outlet temperature, and SPF. A full validation and description of this model is outside of the scope of the present work and will be published separately.

The four unglazed and uninsulated PVT collectors are mounted on the south-facing roof, with empirical thermal and electrical coefficients derived from outdoor testing in Stockholm [12]. Their operation follows a series-regenerative configuration identical to that used in the original multifamily-house study, allowing the system to direct PVT heat either to support evaporator operation or to inject excess heat into the borehole for ground regeneration. The electric and thermal specifications of the PVT collectors are presented in Table 1, where $\eta_0$ is the zero-loss efficiency, $c_1$ the first-order heat loss coefficient, $c_3$ the wind-dependence of the heat loss coefficient, $c_6$ the wind-dependence of zero loss efficiency, $\eta_{el}$ the nominal electrical efficiency, and $P_{max,el}$ the rated electrical power of the PV module.

Table 1. Electric and thermal parameters of the four distinct PVT collectors

| Parameters | S&T | BC-PP | FT | BC-AL-20 |
|---|---|---|---|---|
| $P_{max,el}$ ($W_p$) | 320 | 375 | 400 | 425 |
| $\eta_{el}$ (%) | 19.2 | 20.0 | 20.5 | 17.8 |
| $\eta_{0,th}$ | 0.41 | 0.49 | 0.43 | 0.57 |
| $c_1$ | 13.35 | 13.93 | 34.50 | 27.11 |
| $c_3$ | 4.01 | 4.03 | 6.07 | 5.64 |
| $c_6$ | 0.027 | 0.021 | 0.027 | 0.017 |

Economic boundary conditions are presented in Table 2 [19]. Policies currently applied in Sweden are included, most importantly the 20 % green technology tax credit, capped at SEK 50,000 (~€ 4,500), which reduces the effective PVT investment cost. Electricity costs are calculated using the average day-ahead market price for 2024 [20] and include grid charges, energy taxes, and VAT, resulting in a final consumer electricity cost of approximately 2.0 SEK/kWh (~€ 0.18/kWh). Wholesale electricity price, used for the valuation of electricity sold to the grid, is set to 0.52 SEK/kWh (~€ 0.045/kWh). An annual electricity-price increase of 2 % (matching the inflation rate) is applied. The economic lifetime is assumed to be 20 years for the heat pump, 30 years for the PVT collectors, and 60 years for the borehole, with residual values included where applicable. The total life-cycle cost (TLCC) includes investment, maintenance, electricity purchases, and salvage values, following the method presented in Sommerfeldt and Madani [10].

Table 2. Economic boundary conditions [19]

| Parameter | Value | Unit |
|---|---|---|
| Nominal discount rate | 3 | % |
| Inflation | 2 | % |
| Retail electricity price | 2.0 | SEK/kWh |
| Wholesale electricity price | 0.52 | SEK/kWh |
| Heat pump | 87,500 | SEK |
| S&T PVT | 3,435 | SEK/m$^2$ |
| BC-PP PVT | 4,323 | SEK/m$^2$ |
| FT PVT | 5,765 | SEK/m$^2$ |
| BC-AL-20 PVT | 3,920 | SEK/m$^2$ |
| Borehole (Fixed) | 400 | SEK/m |
| Borehole (Variable) | 5,000 | SEK |

## 4. Results

Figure 4 shows the development of the borehole outlet temperature during the 20-year period and highlights the distinct behavior of the system before and after the introduction of PVT collectors. Throughout the first 10 years, when the system operates without any regeneration, the outlet temperature follows a consistent downward trajectory. The temperature begins at roughly 7.0 °C in the first year and decreases each heating season as the temperature gradient around the borehole develops. By the end of the 2nd year, the temperature is below 6.0 °C, and by Year 10 it reaches approximately 5.6 °C. This continuous decline reflects the long-term thermal imbalance inherent in GSHP-only systems operating in heating-dominated climates. There is no recovery period in which the ground regains the extracted heat, so the borehole field cools progressively with every year of operation.

A very different pattern emerges when PVT collectors are introduced at the beginning of Year 11. The outlet temperature begins to rise immediately, producing a pronounced upward step between Years 11 and 12. The temperature increases from about 5.6 °C at the end of the GSHP-only period to values between 6.2 and 6.4 °C in 2 years, depending on the design of the PVT collector. The BC-PP and BC-AL-20 designs, both characterized by high zero-loss efficiency, deliver the greatest temperature rise, with the finned BC-AL-20 achieving the strongest effect due to its larger heat-transfer surface. After this initial jump, the outlet temperature continues to increase but at a slower rate. By Year 20, the outlet temperature ranges from around 6.4 °C for the S&T collector to nearly 6.6 °C for the BC-AL-20 design. In contrast, the GSHP-only trajectory remains flat at approximately 5.5-5.6 °C over the same period. This difference indicates a sustained long-term thermal benefit of 0.8 K to 1.0 K for the PVT-assisted configurations relative to a system without regeneration.

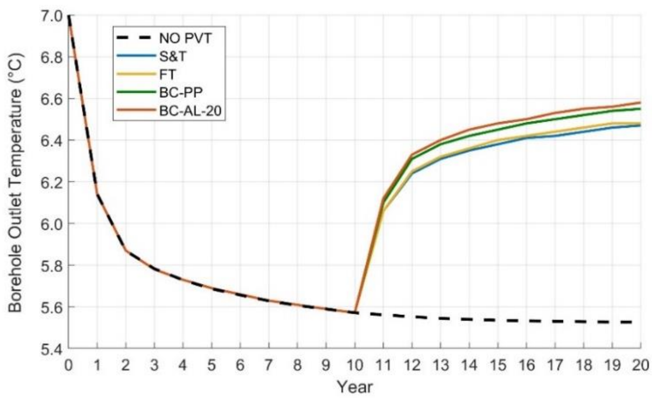


Figure 4. Average borehole outlet temperature over 20 years for the baseline system and for each collector design integrated from year 11 onward.

Figure 5 presents the corresponding evolution of $SPF_{4+}$ across the same 20-year period and makes it possible to interpret how the system's efficiency changes before and after PVT integration. $SPF_{4+}$ starts at about 3.50 in Year 1 and decreases gradually as the system continues operating under a progressively colder ground. The reduction in borehole temperature shown in Figure 4 directly contributes to this decline, as lower entering temperatures increase compressor work and reduce efficiency. By Year 10, $SPF_{4+}$ falls to approximately 3.44, an absolute reduction of about 0.06 or 1.7 % relative to the initial performance.

The introduction of PVT collectors in Year 11 results in an immediate performance shift. All four PVT configurations show a rapid improvement in $SPF_{4+}$ during the first two years after installation. The value increases from the GSHP-only value of 3.44 in Year 10 to approximately 3.46 by Year 12. The magnitude of this improvement corresponds to an absolute gain of 0.02 to 0.03 units, or an increase of 0.6 to 0.9 %. After this initial recovery, the $SPF_{4+}$ continues to rise gradually over the following years, though at a much slower rate than the rapid jump observed immediately after PVT integration. The system eventually stabilizes at long-term values that differ by absorber design. By Year 20, the S&T collector reaches 3.485 and the FT collector approaches 3.495, with the BC-PP and FT designs somewhere in between. In comparison, the GSHP-only case remains near 3.44. The difference between the PVT-assisted and non-regenerated cases therefore ranges from about 1.3 to 1.6 % in Year 20, with the box-channel absorbers producing the highest efficiency due to their greater heat transfer capacity with air.

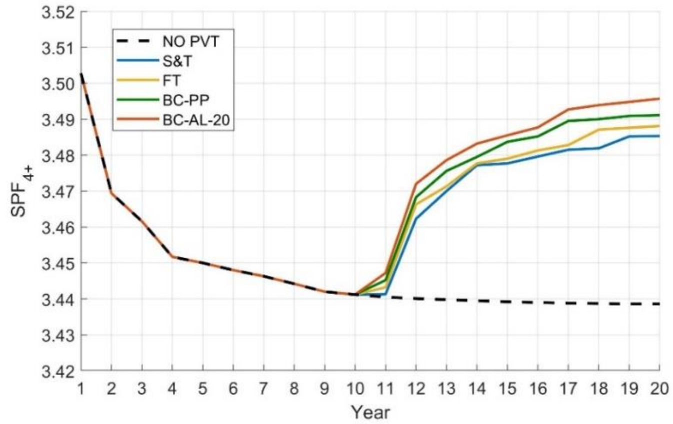


Figure 5. SPF over 20 years for the baseline system and for each collector design integrated from year 11 onward.

Figure 6 summarizes the total heat exchanged with the ground over the 20-year period for the four PVT configurations, together with the Thermal Balance Ratio (TBR %) and the PVT Regeneration Fraction (PVT RF %). The total heat extracted from the borehole is the same across all designs, remaining close to 13 MWh/yr. This consistency reflects the fact that the heating demand and heat pump capacity are identical in all cases; the addition of PVT collectors modifies the thermal balance of the ground but does not change the total heat required by the building.

The heat produced by the PVT collectors, referred to here as $Q_{PVT}$, varies more noticeably with absorber design. The unfinned S&T module produces approximately 137 MWh (456 kWh/m$^2$yr) over 20 years, while the FT, BC-PP, and BC-AL-20 collectors reach between 147 MWh (489 kWh/m$^2$yr), 144 MWh (480 kWh/m$^2$yr) and 152 MWh (505 kWh/m$^2$yr), respectively. Because the injected heat, noted as $Q_{injected}$, is driven directly by the thermal output of the PVT collectors and the operating conditions of the ground-loop heat exchanger, it follows a similar trend. Each design injects between roughly 100 to 110 MWh over the PVT operating decade. When expressed relative to the total heat extracted during the entire 20-year period, the resulting TBR values fall in a narrow band around 40 %, with S&T at 38 %, FT at 41 %, BC-PP at 40 %, and BC-AL-20 at 43 %. These results indicate that over 10 years of PVT operation, the system is able to return approximately two-fifths of the heat previously withdrawn from the ground.

The PVT regeneration fraction, PVT RF %, which expresses $Q_{PVT}$ relative to total heat extracted, shows a wider spread among the collector types. The S&T design delivers roughly 53 % of the total extracted heat, the the BC-AL-20 collector approaches 59 %, with the BC-PP and FT designs somewhere in between. This metric highlights that even though all designs regenerate the ground to a comparable extent, the metallic finned absorber produces more thermal energy overall and therefore has greater potential for long-term regeneration.

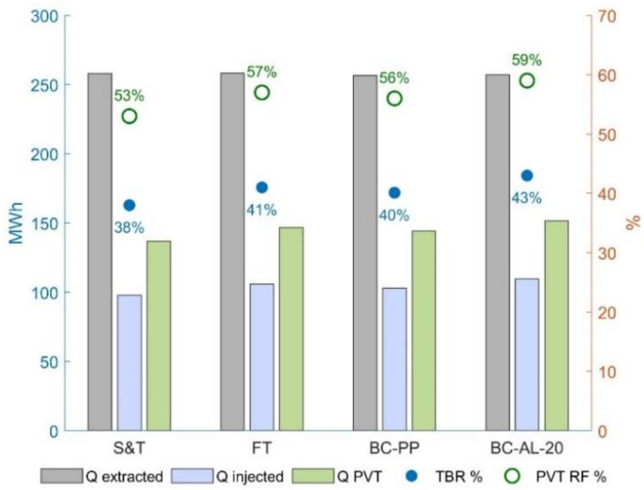


Figure 6. Cumulative thermal balance of the borehole over the 20-year simulation period.

Figure 7 presents the total life-cycle cost (TLCC) of the GSHP system over the 20-year analysis period for the base case without PVT and for the four PVT collector configurations. The TLCC of the GSHP-only scenario is approximately 358 kSEK (32 k€) and serves as the reference for evaluating the economic effect of adding PVT collectors. All PVT-assisted configurations show higher total life-cycle costs, reflecting the additional investment in collectors, mounting structures, piping, and system integration components. Among the PVT options, the S&T collector produces a TLCC of roughly 468 kSEK (42 k€), corresponding to an increase of about 31 % relative to the GSHP-only case. The BC-AL-20 design yields a similar cost level at approximately 473 kSEK (43 k€), representing an increase of around 32 %. The BC-PP absorber reaches roughly 499 kSEK (45 k€), which corresponds to a 39 % rise. The FT collector shows the highest TLCC at 551 kSEK (50 k€), corresponding to an increase of about 54 % compared to the non-PVT scenario.

These differences are primarily driven by the varying investment costs of the collectors. The thermal and operational benefits provided by the PVT collectors, such as improved SPF, reduced auxiliary-heater operation, and partial long-term ground regeneration, do not fully compensate for the higher upfront and replacement costs within the 20-year period considered. The 20-year reduction in total electricity costs is 70–80 kSEK (~€ 6,300 to € 7,200), compared with a PVT investment of 180–265 kSEK (~€ 16,000 to € 24,000). Of the operational savings, roughly 2 kSEK (~€ 170) stem from reduced compressor power, while the remainder is due to avoided grid-electricity purchases and revenues from exported PV electricity. The revenues from exported PV electricity are roughly equivalent to the O&M costs for the PVT system. Consequently, the TLCC variation increases monotonically with collector cost and is only weakly influenced by the performance differences among the absorber designs.

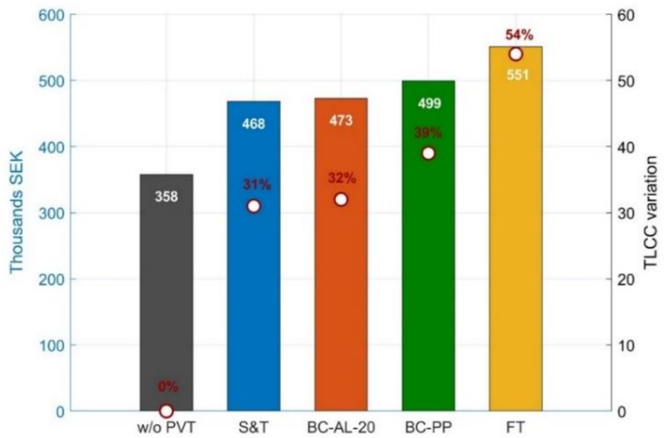


Figure 7. TLCC and TLCC variation with regards to the baseline for all PVT scenarios.

## 5. Conclusions

This study evaluated the technical and economic implications of integrating unglazed PVT collectors into a single-family GSHP system after 10 years of operation without borehole regeneration. The results show that PVT integration provides limited technical benefits when the borehole field is fully sized, and the marginal gains are not enough to offset the additional investment costs under the assumed economic conditions.

With respect to RQ1, adding PVT collectors after a decade of GSHP-only operation produces an immediate improvement in system performance. $SPF_{4+}$ increases by 0.6-0.9 % in the first two years after integration and stabilizes 1.3–1.6 % higher than the GSHP-only case by year 20.

Regarding RQ2, PVT integration alters long-term borehole behavior. After 10 years of continuous cooling, the borehole outlet temperature rises sharply once PVT operation begins and continues to increase throughout the second decade, reaching 6.4–6.6 °C by year 20. Over this period, the system reinjects roughly 40 % of the total heat extracted, with regeneration fractions between 53 % and 59 % depending on the collector type. These results confirm that unglazed PVT collectors can partially restore the thermal deficit accumulated in aging GSHP systems.

For RQ3, the economic analysis shows that the thermal and operational benefits do not outweigh the higher investment costs within the 20-year horizon. The GSHP-only TLCC is approximately 358 kSEK, whereas PVT-assisted systems range from 468 to 551 kSEK (~42k€ to 50 k€), corresponding to cost increases of 31–54 % depending on absorber design. Economic outcomes are therefore dominated by collector cost rather than differences in thermal performance.

Future work should examine GSHP systems design for On/Off operation, which typical have much shorter boreholes due to the lower power capacity expected from the heat pump which is covered by the auxiliary heater. When these systems are replaced with a modern variable speed heat pump, the borehole can be up to 50 % undersized. Such conditions would further increase ground cooling and may shift the technical and economic balance between borehole expansion and PVT-based regeneration.

## 6. References


[1] Swedish Energy Agency, "Statistics Database." Accessed: Dec. 03, 2025. [Online]. Available: https://pxexternal.energimyndigheten.se/pxweb/en/Energimyndighetens_statistikdatabas/Energimyndighetens_statistikdatabas__Officiell_energistatistik__Bostader_och_lokaler/

[2] W. J. Eugster and L. Rybach, "How renewable are borehole heat exchanger systems?," *Bull. d'Hydrogéologie*, vol. 17, pp. 123–132, 1999.

[3] W. J. Eugster and L. Rybach, "Sustainable production from borehole heat exchanger systems," in *World Geothermal Congress 2000*, Kyushu - Tohoku, Japan, 2000, pp. 825–830.

[4] W. Choi, R. Ooka, and Y. Nam, "Impact of long-term operation of ground-source heat pump on subsurface thermal state in urban areas," *Sustain. Cities Soc.*, vol. 38, no. January, pp. 429–439, 2018, doi: 10.1016/j.scs.2017.12.036.

[5] E. Bisengimana, J. Zhou, M. Binama, and Y. Yuan, "Numerical investigation on the factors influencing the temperature distribution of photovoltaic/thermal (PVT) evaporator/condenser for heat pump systems," *Renew. Energy*, vol. 194, pp. 885–901, 2022, doi: 10.1016/j.renene.2022.05.154.

[6] M. Liravi, E. Karkon, J. Jamot, C. Wemhoener, Y. Dai, and L. Georges, "Energy efficiency and borehole sizing for photovoltaic-thermal collectors integrated to ground source heat pump system: A Nordic case study," *Energy Convers. Manag.*, vol. 313, no. January, p. 118590, 2024, doi: 10.1016/j.enconman.2024.118590.

[7] F. Beltran, N. Sommerfeldt, and H. Madani, "Cutting peaks and costs: techno-economic design guidelines for solar PVT and GSHP in land-constrained multi-family buildings," *Energy Convers. Manag. (Accepted 20-10-2025)*, 2025.

[8] N. Sommerfeldt and H. Madani, "Review of Solar PV/Thermal Plus Ground Source Heat Pump Systems for European Multi-Family Houses," no. August 2017, pp. 1–12, 2017, doi: 10.18086/eurosun.2016.08.15.

[9] E. Bertram, J. Glembin, and G. Rockendorf, "Unglazed PVT collectors as additional heat source in heat pump systems with borehole heat exchanger," *Energy Procedia*, vol. 30, pp. 414–423, Jan. 2012, doi: 10.1016/j.egypro.2012.11.049.

[10] N. Sommerfeldt and H. Madani, "In-depth techno-economic analysis of PV/Thermal plus ground source heat pump systems for multi-family houses in a heating dominated climate," *Sol. Energy*, vol. 190, pp. 44–62, Sep. 2019, doi: 10.1016/j.solener.2019.07.080.

[11] N. Sommerfeldt, F. Beltran, and H. Madani, "High Market Potential Applications for PVT with Heat Pumps," 2020, doi: 10.18086/eurosun.2020.05.11.

[12] F. Beltrán, N. Sommerfeldt, J. Eskola, and H. Madani, "Empirical investigation of solar photovoltaic-thermal collectors for heat pump integration," *Appl. Therm. Eng.*, vol. 248, no. March, 2024, doi: 10.1016/j.applthermaleng.2024.123175.

[13] S. Klein, W. A. Beckman, J. Mitchell, J. A. Duffie, and T. Freeman, "TRNSYS 18, A Transient System Simulation Program." Solar Energy Laboratory, University of Wisconsin, Madison, WI, USA, 2017. [Online]. Available: https://sel.me.wisc.edu/trnsys/

[14] F. Beltran and N. Sommerfeldt, "Techno-economic comparison of different solar photovoltaic/thermal (PVT) absorber designs for ground source heat pump (GSHP) integration," in *EuroSun 2024*, 2024.

[15] J. Remund and S. Kunz, "Meteonorm 7.2." 2018.

[16] R. Dott, M. Y. Haller, J. Ruschenburg, F. Ochs, and J. Bony, "The Reference Framework for System

Simulations of the IEA SHC Task 44 / HPP Annex 38 Part B : Buildings and Space Heat Load A technical report of subtask C," 2013.

[17] G. Hellström, "Duct Ground Heat Storage Model - Manual for Computer Code," Department of Mathematical Physics, University of Lund, Sweden, 1989.

[18] J. Claesson and P. Eskilson, "Conductive heat extraction to a deep borehole: thermal analyses and dimensioning rules," *Energy*, vol. 13, no. 6, pp. 509–527, 1988.

[19] M. A. Castañeda Rodas, "Techno-economic analysis of the integration of a PVT array in a long-term operated GSHP for a single-family house in Stockholm," 2025. [Online]. Available: https://www.diva-portal.org/smash/record.jsf?pid=diva2%3A2010309&dswid=6609

[20] Nord Pool Spot, "Elspot Day-Ahead Prices." [Online]. Available: www. nordpoolspot.com

[21] F. Beltrán, N. Sommerfeldt, C. Reichl, and H. Madani, "Cold solar: PVT heat exchanger designs for heat pump integration," *Appl. Therm. Eng.*, vol. 261, no. November 2024, 2025, doi: 10.1016/j.applthermaleng.2024.125020.