Techno-Economic Comparison of Different Solar Photovoltaic/Thermal (PVT) Absorber Designs for Ground Source Heat Pump (GSHP) Integration

Francisco Beltran, Nelson Sommerfeldt

KTH Royal Institute of Technology, Stockholm (Sweden)

Summary

This study assesses the performance of a PVT+GSHP system using four different PVT collectors, each with unique design features, for a multi-family building in Stockholm. Thermal performance coefficients are obtained through outdoor testing of each collector under low-temperature conditions, and incorporated into a comprehensive dynamic system model in TRNSYS. The study varies the design and array size of the PVT collectors and evaluates their impact on the techno-economic performance of the system, considering traditional and undersized borehole fields. Technical performance metrics include annual thermal energy output, seasonal performance factor and back-up heater utilization, and economic performance is assessed with total life cycle cost (TLCC). The results show that when integrating PVTs with GSHP systems, lower collector costs should be prioritized over enhanced thermal performance. Despite the finned designs exhibiting a higher thermal yield (up to 10%) this only improves the seasonal performance factor by 0.6% compared to non-finned designs, but can increase TLCC by up to 5.2%.

Keywords: Solar heat pumps, techno-economic analysis, PVT plus GSHP, borehole regeneration

1. Introduction

The integration of photovoltaic-thermal (PVT) collectors with ground source heat pumps (GSHP) has been shown to reduce borehole length and spacing, significantly decreasing the land area required for the ground heat exchanger (Chhugani et al., 2023; Sommerfeldt & Madani, 2019). One of the key advantages of PVT collectors in this context is the low temperature of the working fluid. This characteristic not only facilitates the simultaneous cooling of the PV cells, thereby enhancing their electrical efficiency, but also improves the thermal performance of the system through increased heat transfer with ambient air (Giovannetti et al., 2019). This has led to the investigation and market development of PVT collectors aimed at improving heat transfer with ambient air, such as by expanding the heat transfer area with the addition of fins. Additionally, the lower temperatures within a GSHP circuit enable the utilization of polymeric materials. However, despite these advancements, there remains a gap in the literature regarding the techno-economic comparison of PVT collectors with different design features for integration with GSHP systems. Existing studies have predominantly focused on performance metrics in isolation, without a comprehensive assessment of the trade-offs between enhanced thermal output, overall system efficiency, and total life cycle cost. Addressing this gap is crucial for informing the design and development of PVT collectors that are optimally suited for GSHP applications. The results of this study are anticipated to enhance the understanding of how PVT collectors should be designed for this particular application, with a focus on technical and economic metrics.

2. Objectives

The objective of this study is to identify the techno-economic optimal PVT collector design for integration into GSHP systems in the Nordic region. This is achieved by answering the following research questions:

- How does PVT design impact thermal energy generation in a PVT+GSHP system?
- How is the technical system performance impacted by the various PVT designs?
- Is there an economically preferred design approach for PVT as applied to GSHP?

10.18086/eurosun.2024.02.01 Available at http://proceedings.ises.org

3. Methods

This study employs a comprehensive dynamic system modeling approach to evaluate the integration of different PVT absorber designs with a ground source heat pump (GSHP) system. The methodology begins with outdoor testing to obtain empirical thermal performance coefficients for the studied PVT designs. These coefficients are then incorporated into a TRNSYS simulation model tailored to represent a multi-family building in Stockholm. By simulating various configurations of PVT arrays and borehole fields, the model assesses both the technical and economic performance of the system. This ensures that the analysis captures the nuanced trade-offs between thermal energy output, system efficiency, and total life cycle costs across different design scenarios.

The case study for the dynamic modelling is based on the PVT + GSHP TRNSYS model developed by Sommerfeldt & Madani, (2019), as shown in Fig. 1. It represents a typical multi-family house in Stockholm built between the years 1985 and 2005 with 2,000 m^2 of heated floor area. The building's energy needs are 125 kWh/m^2-yr for space heating, 38 kWh/m^2-yr for domestic hot water, and 30 kWh/m^2-yr for electricity. The system includes a variable-speed ground source heat pump with a capacity of 52 kW (B0/W35) at 3600 RPM. The baseline ground heat exchanger consists of 12 parallel U-tube boreholes, each 300 meters long and spaced 15 meters apart. The PVT array features 48, 96, and 144 (maximum array size assumed to fit on the roof) connected in a series/regenerative configuration with the GSHP. The PVT collectors are modeled using Type 203 (Chhugani et al., 2021), which relies on the empirical thermal performance coefficients of the collectors.

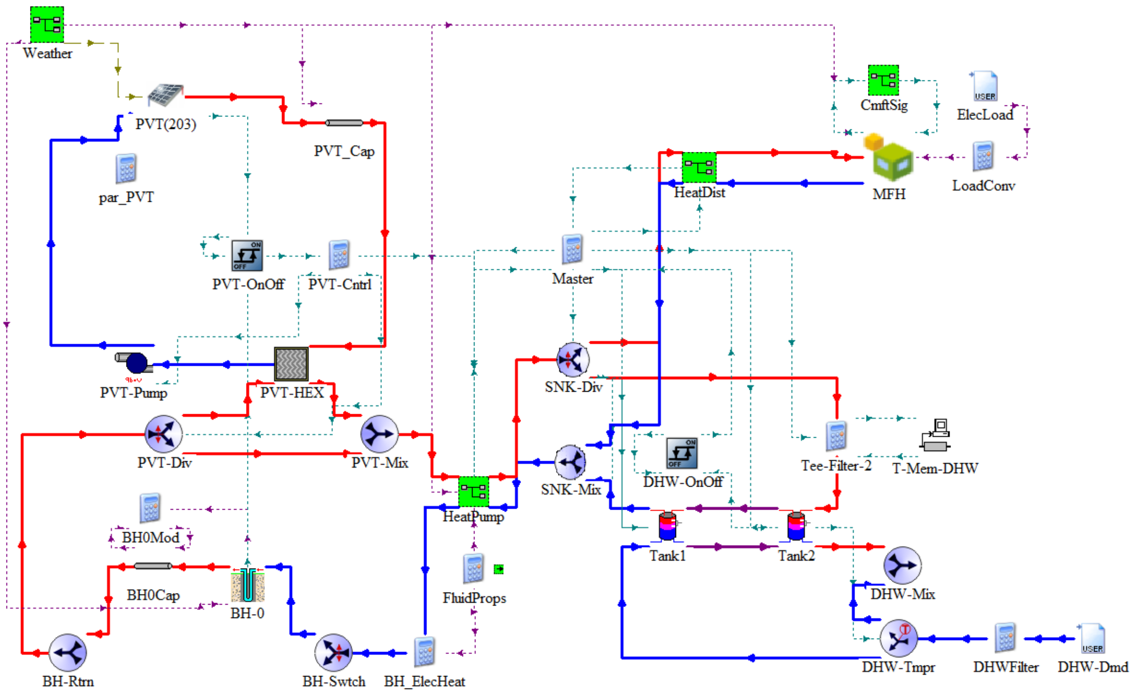

Fig. 1. PVT + GSHP simulation model in TRNSYS

The studied collectors are a sheet and tube (S&T), box-channel polypropylene (BC-PP), finned-tube (FT), and box-channel aluminum with 20 mm fins (BC-AL-20), which are described in detail in (Beltrán et al., 2024). A representation of the different PVT designs can be seen in Fig. 2. The collectors are evaluated based on four key metrics: specific annual thermal energy output (in kWh/m^2-yr), seasonal performance factor (SPF$_{4+}$), utilization rate of direct electric backup heater (in percentage of total thermal energy delivered), and total life cycle cost (TLCC) in Euros. These results are benchmarked against a baseline GSHP system with a borehole field comprising 12 boreholes, each 300 m deep, spaced 15 meters apart and without PVTs. Additionally, the same PVT systems are coupled with an undersized borehole field of 6x300 m boreholes and 5 m spacing to evaluate if the cost-benefit balance changes.

The seasonal performance factor is calculated according to eq.1, following the methodology established by Sommerfeldt and Madani (Sommerfeldt & Madani, 2019). The SPF$_{4+}$ metric used in this study is a hybrid of

SPF4, as defined by Nordman et al. (Nordman et al., 2012), and SHP+, as presented by the IEA's T44A38 program (Hadorn, 2015).

$$SPF_{4+} = \frac{Q_{sh}+Q_{dhw}}{E_{hp}+E_{p,src}+E_{p,snk}+E_{bb}+E_{b,dhw}+E_{p,pvt}} \quad \text{(eq. 1)}$$

The total life cycle cost is used to compare the economic performance of the PVT+GSHP systems and is described by eq. 2. The main components of the TLCC are investments (I_x), operations and maintenance (OM_x), and residual value (RV_x). The nomenclature for both equations can be found in Tab. 1, whereas the economic boundary conditions are presented in Tab. 2.

$$TLCC_{PVT+GSHP} = I_{HP} + I_{BH} + I_{PVT} + OM_{EL} + OM_{EQ} - RV_{PVT} - RV_{BH} \quad \text{(eq. 2)}$$

Tab. 1: Nomenclature for equations 1 and 2

Parameter	Symbol	Unit
Thermal energy for space heating	Q_{sh}	kWh_{th}
Thermal energy for domestic hot water	Q_{dhw}	kWh_{th}
Electric energy for heat pump compressor	E_{hp}	kWh_{el}
Electric energy for borehole circuit pump (source)	$E_{p,src}$	kWh_{el}
Electric energy for heat delivery pump (sink)	$E_{p,snk}$	kWh_{el}
Electric energy for backup heat pump heater	E_{bb}	kWh_{el}
Electric energy for backup tank heater	$E_{b,dhw}$	kWh_{el}
Electric energy for PVT circulation pump	$E_{p,pvt}$	kWh_{el}
Investment costs – heat pump	I_{HP}	€
Investment costs – boreholes	I_{BH}	€
Investment costs - PVT	I_{PVT}	€
Operation and maintenance – electricity purchases	OM_{EL}	€
Operation and maintenance – system equipment	OM_{EQ}	€
Residual value - PVT	RV_{PVT}	€
Residual value - boreholes	RV_{BH}	€

Tab. 2: Economic boundary conditions

Parameter	Unit	Value
Purchase electricity price	€/kWh	0.14
Wholesale electricity price	€/kWh	0.052
Heat pump cost (w/VAT)	€	32,586
S&T PVT cost	€/m^2	312.3
BC-PP PVT cost	€/m^2	393.0
FT PVT cost	€/m^2	524.1
BC-AL-20 cost	€/m^2	356.4
PVT fixed cost	€	11,300
PVT variable cost	€/collector	260.8

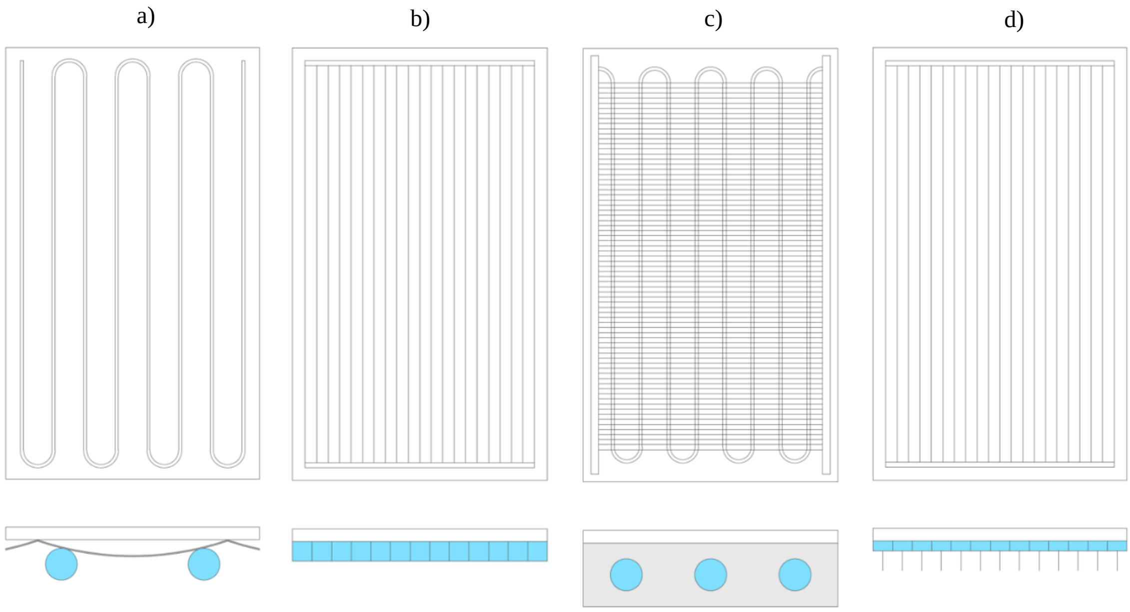

Fig. 2. Representation of a) S&T b) BC-PP c) FT d) BC-AL-20 (Beltrán et al., 2024)

The thermal performance coefficients of the studied PVT collectors are derived at an outdoor testing facility in Stockholm, as described in Beltrán et al., (2024). The thermal output of the PVT collectors is measured under a wide range of operating and weather conditions, and a linear multivariable regression analysis is used to derive the empirical thermal performance coefficients of each collector according to eq. 3, a simplified form of the ISO 9806:2017 standard equation for liquid heating collectors (ISO, 2017). The zero-loss efficiency (η_0), first-order thermal loss coefficient (c_1), the wind dependence of the heat loss coefficient (c_3), and the wind dependence of the zero-loss efficiency (c_6) for each PVT collector design are presented in Tab. 3. T_a is the ambient temperature, T_m the mean fluid temperature, G the global irradiance on the plane of the array and u the wind velocity.

$$\dot{q}_{th} = \eta_0 G - c_1(T_m - T_a) - c_3 u(T_m - T_a) - c_6 uG \qquad \text{(eq. 3)}$$

Tab. 3: Thermal performance characteristics of the different PVT collectors

Coefficients	S&T	BC-PP	F&T	BC-AL-20
Area [m^2]	1.67	1.88	1.99	1.95
η_0	0.410	0.490	0.428	0.566
c_1 [W/(m^2.K)]	13.345	13.925	34.502	27.105
c_3 [J/(m^3.K)]	4.012	4.026	6.066	5.637
c_6 [s/m]	0.027	0.021	0.027	0.017

4. Results

Fig. 3A shows the average specific annual thermal energy output of the different collector designs throughout the 20-year time span, for varying PVT array sizes. As expected, the finned designs provide a higher thermal energy output than the non-finned designs due to the enhanced heat capture from ambient air. When compared with the S&T, the FT and BC-AL-20 absorbers generate 7.4% and 10.0% higher specific annual thermal energy output respectively, for the 48 PVT array size. The thermal output of the BC-PP is higher than the S&T thanks to a higher contact area between the fluid and rear side of the PV panel, but lower than the finned designs due to a lower heat exchange area with ambient air. As the array size increases, there are diminishing returns on the thermal output due to the increased borehole temperature, and with 144 collectors the specific annual output is similar across designs.

Fig. 3B shows that the addition of 48 PVT of the S&T design can improve the seasonal performance factor by 1.9% compared to the case with no PVTs, while the finned designs can improve SPF by 2.5%. This shows that the effect of the different PVTs on SPF is similar, regardless of the absorber design. Increasing the PVT array size to 96 or 144 collectors shows additional improvements in SPF but with diminishing returns (improvement of 1.5% and 0.9% respectively for the S&T design). A similar effect is seen in the back up heater use, as shown in Fig. 3C. By adding 48 of the S&T PVTs, the back-up heater use is negligibly reduced from 2.21% to 2.01% of the total space heating demand. By changing to FT or BC-AL-20, a minimum value of 1.96% is achieved. Due to the low impact that PVT collectors have on the overall system efficiency with the baseline borehole field, the TLCC of a PVT+GSHP system is higher than that of a GSHP-only system for all the considered PVT designs (Fig. 3D).

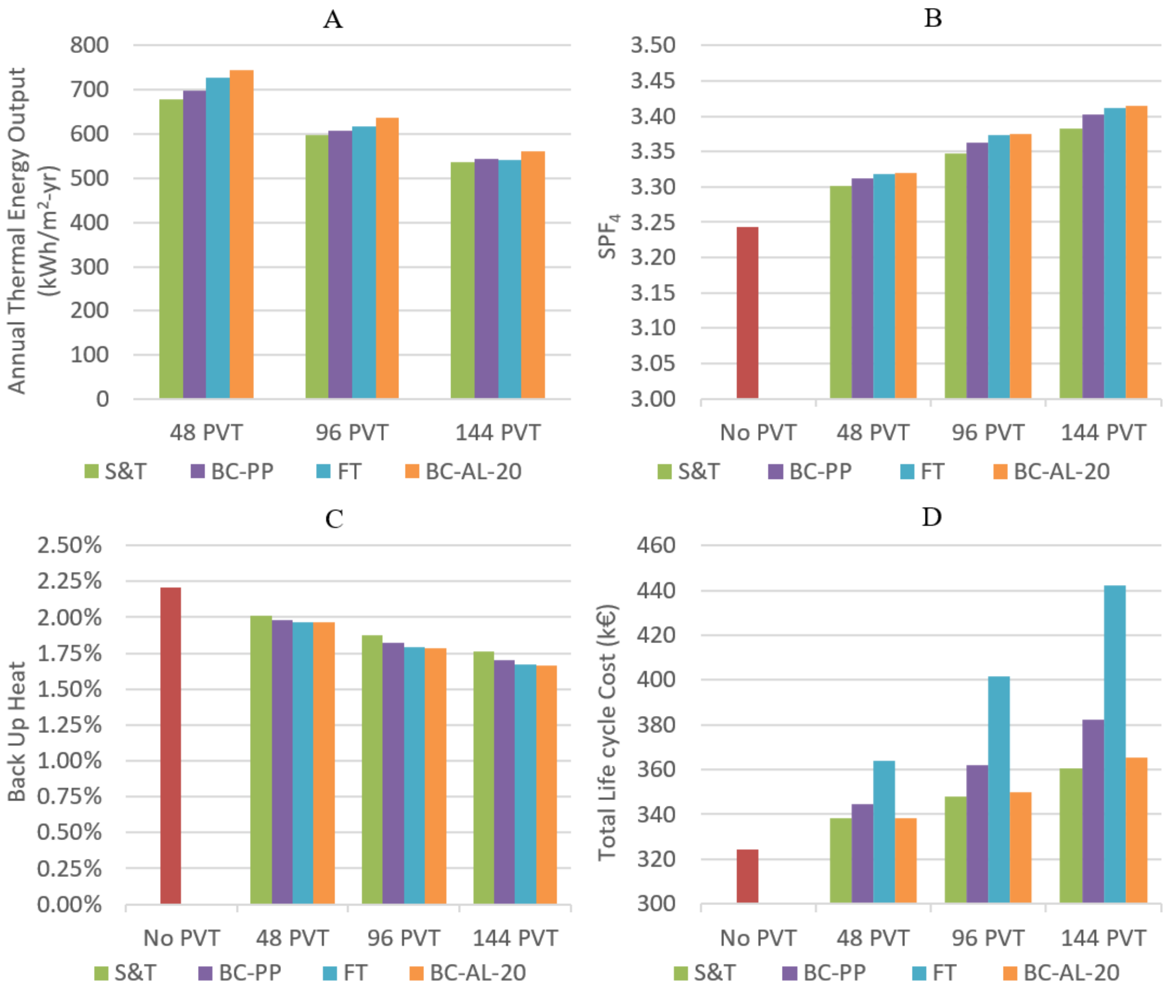

Fig. 3. A) Annual thermal energy output B) SPF C) Back up heater use and D) TLCC of the different PVT collector designs for varying array sizes and the baseline borehole field. *(note that y-axis does not start at zero for SPF and TLCC)*

Since one of the main benefits of PVTs on GSHP systems is the potential to reduce borehole field size and/or regenerate degraded borehole fields, an undersized borehole field of 6x300 m boreholes with 5 m spacing is also simulated. The results in Fig. 4A show that the specific thermal energy output of the PVT collectors connected to an undersized borehole field is 40-45% higher than for the baseline borehole field. This can be explained by the fact that in an undersized borehole field, the temperatures in the ground are lower, and therefore the heat capture potential of the collector is considerably higher, as seen in Fig. 5. In terms of PVT yields for the 48 PVT case, the S&T produces 1,030 kWh/m^2-yr, with the FT and BC-AL-20 producing 1,068 kWh/m^2-yr and 1,078 kWh/m^2-yr respectively. The specific thermal production is almost equal among the different designs since the less efficient PVT collectors result in lower ground temperatures, increased temperature differences between ambient and fluid, and therefore comparable thermal generation. It is also worth noting how the thermal production drops as array sizes increase. The specific thermal yield of 144 PVTs with an undersized borehole field is lower than that of the baseline borehole field with 48 PVTs

The impact on SPF and back up heater use is higher in the case of an undersized borehole field, as can be observed in Fig. 4B and Fig. 4C. The addition of 48 PVTs of the S&T collectors can improve the seasonal performance factor by 7.7% and reduce back up heat from 6.0% to 4.7% of the total space heating supply. As observed for the case of the baseline borehole field, there is a negligible difference in system efficiency between the different designs, with all SPFs between 2.83 and 2.88, and back up heat supply between 4.7% and 4.4%. Increasing the array size to 96 and 144 PVT collectors has diminishing returns, with the SPF of a system with 96 of the BC-AL-20 (187 m^2) being almost equal to that of a system with 144 of the S&T or BC-PP collectors (240-244 m^2).

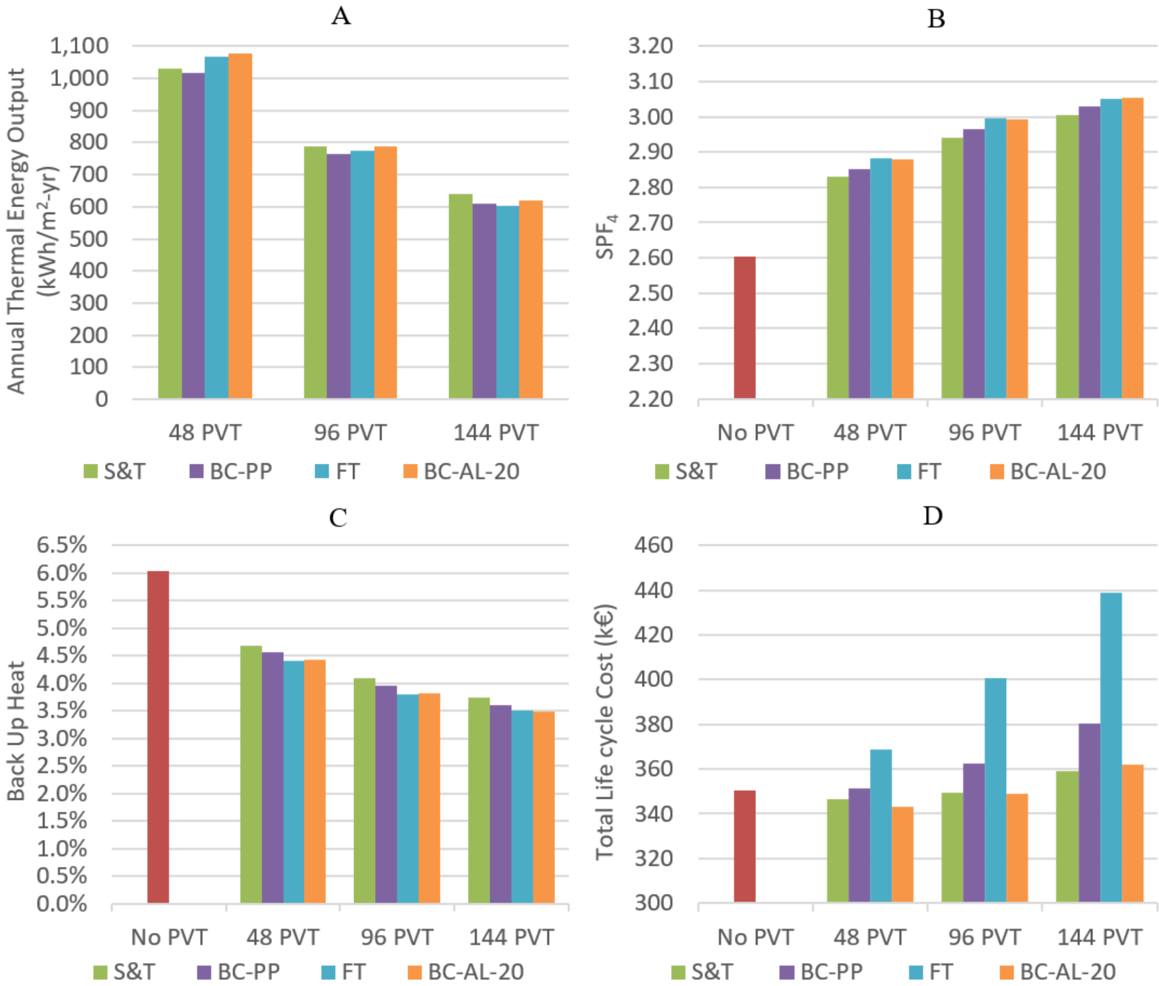

Fig. 4. A) Annual thermal energy output B) SPF C) Back up heater use and D) TLCC of the different PVT collector designs for varying array sizes and an undersized borehole field. *(note that y-axis does not start at zero for SPF and TLCC)*

There is a clear shift in the economic balance when adding PVT collectors to a GSHP system with an undersized borehole field. Fig. 4D shows that the TLCC of a system without PVT is the same as for a system with 48 of the BC-PP PVT collectors. If we consider adding 48 of the S&T or BC-AL-20 collectors, TLCC can be reduced by 1.2% and 2.0%, making it economically more attractive than the case without PVT. However, the more expensive manufacturing process of the FT design is not cancelled out by the higher thermal energy output and SPF improvement, which results in a TLCC 5.2% higher than for the case without PVT. Lower costs are achieved for the S&T and BC-AL-20 designs when considering 96 PVTs, but in all other cases the PVT + GSHP system ends up being more expensive than the GSHP-only. The lowest cost system overall is the traditionally sized GSHP without PVT.

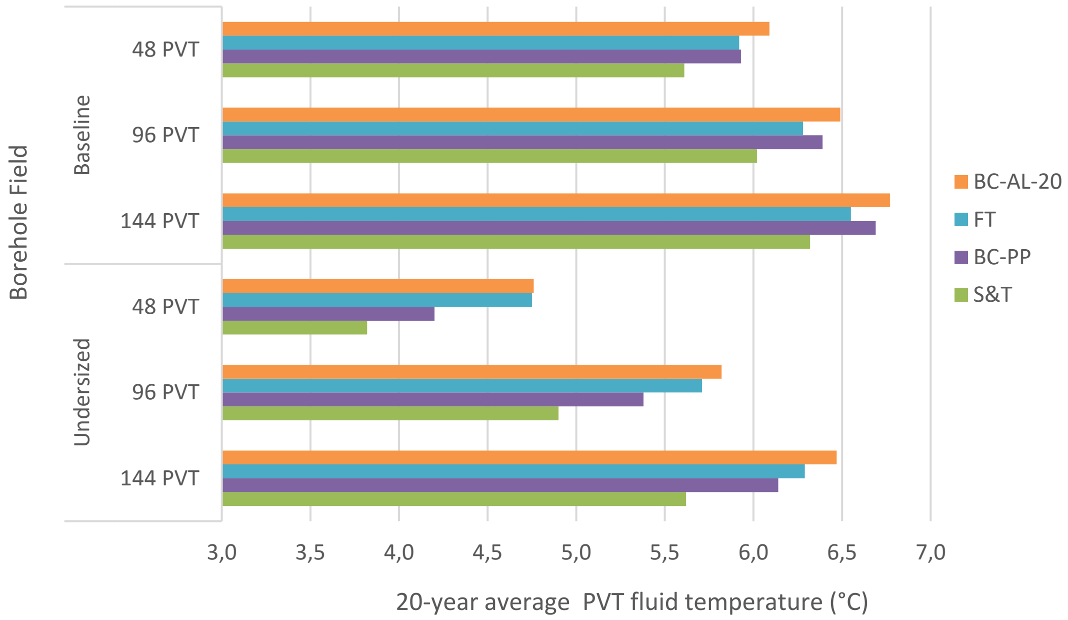

Fig. 5. 20-year average fluid temperature in the PVT collectors for baseline and undersized borehole fields across different PVT array sizes (48, 96, and 144 PVTs).

5. Conclusions

The results of this work show that when integrating PVT collectors with ground source heat pump systems it is necessary to prioritize lower capital costs over enhanced thermal performance. Although the finned designs yield a higher annual thermal energy output, it does not translate to an equivalent improvement in system efficiency. Fins are a positive feature for this application, only if they can be added at a low cost, as is the case of the BC-AL-20.

It has also been shown that there is no need for large PVT arrays since the best economic results were achieved with the lowest array size due to the higher specific heat output. Besides, considering only technical performance, increasing the array size has diminishing returns on SPF improvement and back up heat reduction.

Another important aspect to consider is material selection. The only plastic absorber considered in the study is the BC-PP, and the annual thermal energy output is higher than for the non-finned metallic counterparts, but it comes at a higher manufacturing cost. However, it is still a cheaper option than the finned designs.

Finally, it is confirmed that there is a greater potential for PVT to be integrated into systems with undersized borehole fields than there is in new systems with a well-dimensioned ground heat exchanger. Adding PVT collectors can yield positive economic results in those cases.

6. Acknowledgements

This study was conducted as part of the *Smart Renovation Strategies for Sustainable Electrification* project (SmartReno SE - Project No. P2023-01509), funded by the Swedish Energy Agency under the ReBygg Program. The authors also gratefully acknowledge the financial support provided by Nordic Energy Research, which facilitated an exchange to the Norwegian University of Science and Technology (NTNU), where an important portion of this work was carried out.

7. References

Beltrán, F., Sommerfeldt, N., Eskola, J., & Madani, H. (2024). Empirical investigation of solar photovoltaic-thermal collectors for heat pump integration. *Applied Thermal Engineering*, *248* (December 2023). https://doi.org/10.1016/j.applthermaleng.2024.123175

Chhugani, B., Pärisch, P., Helmling, S., & Giovannetti, F. (2023). Comparison of PVT - heat pump systems with reference systems for the energy supply of a single-family house. *Solar Energy Advances*, *3* (December 2022), 100031. https://doi.org/10.1016/j.seja.2022.100031

Chhugani, B., Pärisch, P., Kirchner, M., Littwin, M., Lampe, C., & Giovannetti, F. (2021). *Model Validation and Performance Assessment of Unglazed Photovoltaic-Thermal Collectors with Heat Pump Systems*. 1–12. https://doi.org/10.18086/eurosun.2020.05.13

Giovannetti, F., Lampe, C., Kirchner, M., Littwin, M., Asenbeck, S., & Fischer, S. (2019). Experimental investigations on photovoltaic-thermal arrays designed for the use as heat pump source. *Proceedings of the ISES Solar World Congress 2019 and IEA SHC International Conference on Solar Heating and Cooling for Buildings and Industry 2019*, 177–188. https://doi.org/10.18086/swc.2019.05.03

Hadorn, J. (2015). *Solar and Heat Pump Systems for Residential Buildings*.

ISO. (2017). *ISO 9806:2017 Solar energy - Solar thermal collectors - Test methods*.

Nordman, R., Kleefkens, O., Riviere, P., Nowak, T., Zottl, A., Arzano-Daurelle, C., Lehmann, A., Polyzou, O., Karytsas, K., Riederer, P., Miara, M., Lindahl, M., Andersson, K., & Olsson, M. (2012). *SEasonal PErformance factor and MOnitoring for heat pump systems in the building sector SEPEMO-Build: FINAL REPORT*.

Sommerfeldt, N., & Madani, H. (2019). In-depth techno-economic analysis of PV/Thermal plus ground source heat pump systems for multi-family houses in a heating dominated climate. *Solar Energy*, *190*, 44–62. https://doi.org/10.1016/j.solener.2019.07.080