High Market Potential Applications for PVT with Heat Pumps

Nelson Sommerfeldt, Francisco Beltran and Hatef Madani

KTH Royal Institute of Technology, Stockholm (Sweden)

Abstract

Within the heat pump sector, there are applications where photovoltaic/thermal (PVT) collectors can offer greater value with lower investment costs than the current alternatives. The first is ground source heat pumps (GSHP) with under dimensioned boreholes. The second is a solar source heat pump (SSHP) where the PVT collectors are a replacement for the traditional air heat exchanger in an air source heat pump (ASHP). Complete systems models for a multi-family house are simulated in TRNSYS to determine seasonal performance factors (SPF), which are then compared technically and economically to each respective alternative. A 156 m^2 PVT array is capable of improving the SPF of a degraded GSHP by 30%, the same gains as drilling additional boreholes but at a lower cost. The SSHP with a 235 m^2 PVT array can reach an SPF of 2.6, comparable to the performance of an ASHP, but has the cost of a GSHP. Already today, PVT can economically compete with borehole drilling for GSHP and the SSHP concept shows enough market potential to warrant investment and development towards broader adoption.

Keywords: PV/thermal, Solar Hybrid, Solar Heat Pump, TRNSYS

1. Introduction

Relative to solar thermal (ST) and photovoltaics (PV), the market penetration of PV/thermal (PVT) hybrid collectors has been extremely limited (Weiss and Spörk-Dür, 2019). Recent cost reductions in photovoltaic (PV) modules have made PVT collectors more interesting economically, particularly when combined with heat pumps in a series configuration (Sommerfeldt and Madani, 2016). Previous studies have found that the primary benefit of adding PVT collectors to ground source heat pumps (GSHP) in a series/regenerative configuration has been the reduction of required borehole length (Bertram et al., 2012; Emmi et al., 2015; Eslami-nejad et al., 2009). While savings can be made on the borehole drilling, the high cost of the PVT systems currently make PV-only systems more economically interesting for new installations (Sommerfeldt and Madani, 2019). However, with strategies for reduced collector costs due to standardization and scaling (Thür et al., 2018) and the projected growth of the European heat pump market (EHPA, 2019), unglazed PVT can find interesting market opportunities.

One such possibility is the future GSHP retrofit market. After 20 years of heat extraction, the temperature in ground heat exchangers (GHE) is reduced, which is typically designed into the original system. However, when it is time to replace the heat pump with a new, more efficient unit, the higher efficiency combined with the already degraded boreholes means the GHE will be undersized. The traditional solution would be to increase the size of the GHE, assuming the necessary land area is available and the owner is accepting of damage to their garden. PVT offers an alternative that could be cost effective, reduces impact on the property, and increases renewable energy utilization in the building. Markets with a longer history of GSHP installation, like Austria, Sweden, and Switzerland, are starting to grapple with the retrofit issue, and the increased installations of GSHP in the 2010’s means that many other European countries will come to the same challenges in 10-15 years (EHPA, 2019).

Another potential application are solar sourced heat pumps (SSHP) as a replacement for air source heat pumps (ASHP). ASHP are far more common than GSHP due to their lower costs and ease of installation, however the need for a noisy heat exchanger on the building’s exterior is a drawback. PVT could replace this heat exchanger and provide energy to the heat pump from both the sun and air. A recent study demonstrated the

doi:10.18086/eurosun.2020.05.11 Available at http://proceedings.ises.org

potential for insulated PVT collectors to meet winter loads at -10 °C, concluding that the system concept showed promise but should use uninsulated collectors to improve heat transfer between the air and working fluid (Schmidt et al., 2018). A further improvement could be forced convection on the rear side of the PVT so long as the fan speeds are not so high that they produce the same noise problems as ASHP. The resulting system could be a more aesthetically attractive and quieter alternative to ASHP, which has a much larger market potential than GSHP and would help build the scale PVT needs to achieve the necessary cost reductions.

2. Objective and Methodology

This is a market feasibility study with the aim of identifying low-barrier entry points for PVT collectors as an integral part of heat pump systems. This is achieved by benchmarking technical performance with traditional solutions and comparing the initial investment costs. Two applications are investigated; PVT in support of older GSHPs with degraded boreholes and PVT in a SSHP configuration. Focus is on the Nordic market, which has the highest per capita rate of heat pump installations in Europe (EHPA, 2019), with climate and economic boundary conditions from Stockholm, Sweden.

For the GSHP renovation test, the borehole length is reduced by 60% from a standard design and simulated for 10 years, resulting in the reduced ground temperatures and high backup heater use typical of older heat pumps. At this point, PVT arrays or additional boreholes are added and the simulation continued for another 10 years. For the SSHP test, the same variable speed heat pump model is used but with a bypass around the boreholes. Modifications to the PVT collector are tested towards the goal of increasing heat transfer with the air, such as increasing surface area of the heat exchanger and introducing forced convection. Simulation of the fans is done by increasing the convection coefficient on the rear side of the PVT in conjunction with multiple fan speeds and air velocities.

The technical performance for both tests are demonstrated with seasonal performance factor (SPF_{4+}), given by Equation 1 and includes: total space heat (Q_{sh}) and domestic hot water (Q_{dhw}) demand of the building, electricity supply to the compressor (E_{hp}), and parasitic loads [circulations pumps for source ($E_{p,src}$) and sink ($E_{p,snk}$) loops, supporting heater for the heat pump (E_{bb}) and the hot water tank ($E_{b,dhw}$), the PVT circulation pump ($E_{p,pvt}$), and the PVT fans ($E_{f,pvt}$)].

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

3. Model Description

The exploratory nature of this study drives an approach that is adopted from previous work, requiring minimal model development while meeting the objectives. Simulations are performed with a full solar heat pump model in TRNSYS17 (Klein et al., 2009), shown in Fig. 1, which includes a multi-zone building, ground source heat pump, boreholes, and PVT collectors integrated in series. A full description of the TRNSYS model and economic assumptions can be found in (Sommerfeldt and Madani, 2019) and is therefore only briefly described here with a focus on modifications specific to the study. It is worth noting however that all costs are reported without VAT or local subsidies, and that prices are taken from the 2019 Swedish market and converted into Euros with a 10:1 ratio.

3.1 System Model

The target building is a typical multi-family house located in Stockholm, requiring 125 kWh m^{-2} yr^{-1} of space heating and 38 kWh m^{-2} yr^{-1} of domestic hot water. The high level of space heating is common among buildings from the 1980's and earlier without energy efficiency retrofits. The same 88 kW, variable speed, brine-to-water heat pump is applied in both cases. The maximum PVT array size is 144 collectors, equaling 235 m^2 and 40 kW_p and are connected in series via a plate heat exchanger as shown in Fig. 1. The borehole circuit includes a bypass valve where the boreholes can be removed from the circuit. The bypass is only used for isolating the PVT to create a SSHP configuration, as is not part of a control strategy with GSHP.

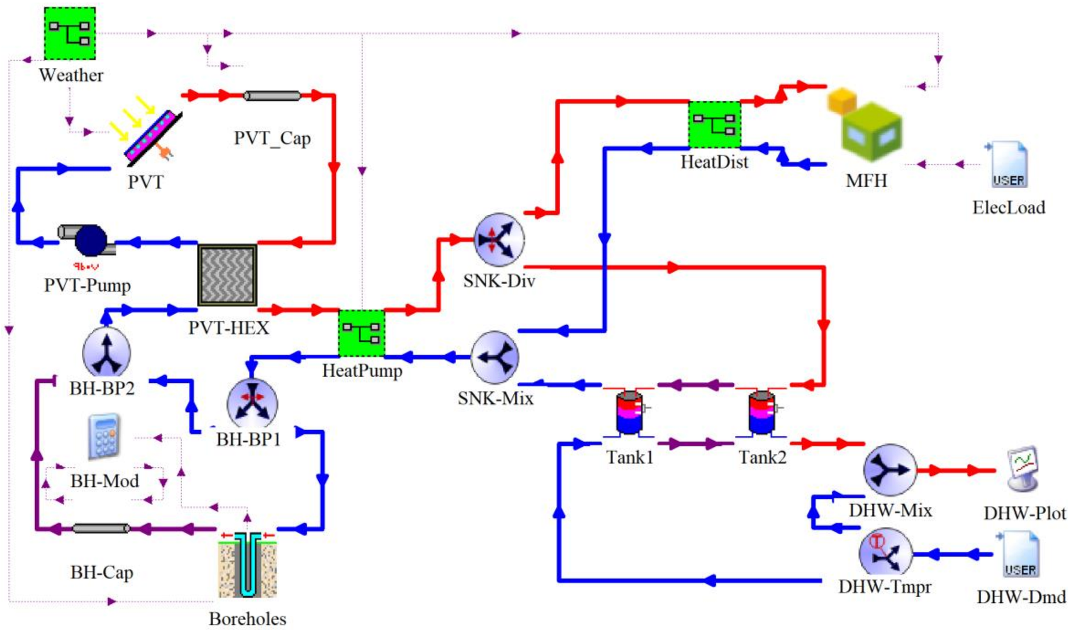

Fig. 1: TRNSYS model representing the GSHP and SSHP systems

3.2 Borehole Fields

Type 557a, based on the Duct Storage Model (Hellström, 1989), is used to model the borehole field with fluid capacity and residency modeled using a modified version of the method proposed by Pärisch et al. (2015). The model assumes equidistant spacing between boreholes (triangular pattern) inside of a cylindrical volume. This approach makes parametric studies inside TRNSYS convenient and has been shown to perform well against g-function based models with rectangular drilling patterns (Fossa and Minchio, 2013; Spitler et al., 2009).

The baseline borehole field is sized using a modified ASHRAE approach (Rolando et al., 2015) and has a total length of 3600 m (12 boreholes, 300 m deep, 20 m spacing). The reduced field removes seven of the 12 holes for a total length of 1500 m, but maintains the 300 m depth and 20 m spacing.

In cases where additional boreholes are drilled, the reduced field is simulated for 10 years. The next 10-year simulation is prepared with the full 12 boreholes, but is precooled until the average soil temperature at the center of the soil volume matches the final temperature from the first 10 years. The main limitation to this approach is the inability to control the undisturbed ground temperature in the soil volume that contains new boreholes. A temperature gradient does exist in the precooled soil volume, however it is unknown to what degree this would match a real world temperatures of soil around an existing borehole field. Given the scope is limited to economic feasibility, the uncertainty in soil temperatures is assumed to be within acceptable limits.

3.3 PVT Collectors

The PVT collectors are simulated using Type 560, a theoretical model allowing customized geometry and external convection coefficient. The baseline design is based on a tested and validated prototype fin-and-tube PVT collector (Sommerfeldt and Ollas, 2017). This model is applied to the GSHP and SSHP systems, but the SSHP application also makes three modifications aimed at increasing heat exchange with the air:

1. Increasing the tube count to represent a wetted-absorber design.
2. Increasing the external convection coefficient to represent forced convection with fans.
3. Increasing the internal convection coefficient to represent changes to heat exchanger geometry.

A wetted absorber design increases the heat exchange area of the collector fluid with the PV cells and air. Type 560 is based on the Hottel and Whillier model (Duffie and Beckman, 2013; Hottel and Whillier, 1955) derivation of solar collector performance, meaning that it is limited to fin-and-tube designs. To model a wetted absorber, it is possible to use many small tubes such that the fins become almost non-existent, which produces comparable results to a 1D model (Pressiani et al., 2016). With 240 tubes at 0.002 m diameter, the cross-sectional area of the tubes remains similar to the current design. The fins also become 0.002 m thereby representing a 50% wetted absorber. Since an actual collector design has not be realized yet, this is assumed to be a reasonable design assumption given that there are box-channel designs currently on the market with greater contact areas between the fluid and the absorber.

There has been extensive work reviewing convection coefficients related to wind, and Sartori (2006) summarized the models most relevant to solar collectors, i.e. forced air flow across flat surfaces. The conclusions produced three equations considering wind velocity and swept length for laminar, mixed, and turbulent flows. This study assumes turbulent flow for the backside of the collector, and is determined with Equation 2. Equivalent air speeds of 6 and 12 m/s are tested with a PVT collector length of 1.6 m, corresponding to convection coefficients of 21.9 and 38.1 W m^{-2} K^{-1}. The forced convection is only applied when the heat pump is operating. When not applied, natural convection with a coefficient of 6.0 W m^{-2} K^{-1} is assumed.

$$h_c = 5.75 V^{0.8} L^{-0.2} \quad \text{(eq. 2)}$$

4. Results and Discussion

4.1 Drilling and PVT

Figure 2 shows the development of SPF_4 in the GSHP over the 20-year simulation. The baseline system has a 20-year average SPF_{4+} of 3.3, which is expected for an older building with high power and heating supply temperatures. The reduced boreholes require considerable backup heater use, resulting in an SPF_{4+} that starts at 2.9 in year one and falls to 2.3 in year 10 as the surround soil cools. When the PVT array is added, backup heater use is reduced and within four years, the boreholes reach steady state. Three array sizes are tested, 48, 96 and 144 PVT collectors, with steady state SPF_{4+} of 2.8, 2.9 and 2.9, respectively. Drilling 2100 m of additional borehole in year 10 has a similar resulting SPF_{4+} of 2.9. This result suggests that from a technical perspective, PVT collectors could provide a similar benefit to an undersized GHE as additional drilling.

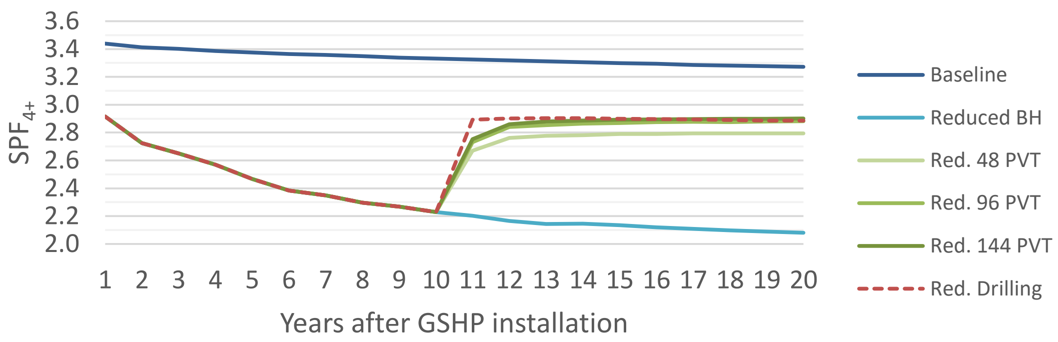

Fig. 2: SPF_4 of the degraded GSHP with PVT added in Year 10

A regression model of borehole costs derived from a survey of Swedish drillers suggests that the cost of drilling a new borehole field can be estimated at 20 € m^{-1} of total length (Mazzotti et al., 2018) with an additional 10 € m^{-1} for piping materials and commissioning. Therefore, the additional 2100 m of borehole in this system would cost €63k, assuming there are no additional costs associated with expanding the existing system. By comparison, the 48, 96, and 144 PVT collector systems would cost approximately €40k, €70k, and €100k, respectively. This is particularly noteworthy given that a 96-collector system can deliver nearly identical technical performance as the drilling for only 10% higher cost. It then has the additional benefits of not disturbing the land with drilling equipment, stabilizing borehole temperatures from further degradation, and generating renewable electricity worth approximately €15k over its 30-year lifetime.

Given that the Swedish market conditions can be characterized by low drilling and electricity prices, these results can be interpreted as somewhat conservative. For example, drilling prices up to 100 € m^{-1} have been applied to other European markets (Helpin et al., 2011), which makes PVT a far better economic choice. Higher electricity prices and generally stronger solar resources will also lead to a higher value of PV generation, further improving the economic conditions.

4.2 SSHP

The SSHP system uses 144 PVT collectors considering four designs;

- Baseline: the original PVT collector design with six runners without forced convection
- Abs: the modified PVT design with wetted absorber, without forced convection
- Low: the modified PVT design with 6 m/s forced convection
- High: the modified PVT design with 12 m/s forced convection

The results in Figure 3 show that the design changes dramatically improve SPF_{4+} up to 2.6. The largest improvements however come from the heat exchanger modification and the introduction of forced convection, whereas increasing fan speeds have diminishing returns. These results are comparable to other indirect SSHP studies in cold climates, suggesting the system is operating correctly (Chu and Cruickshank, 2014).

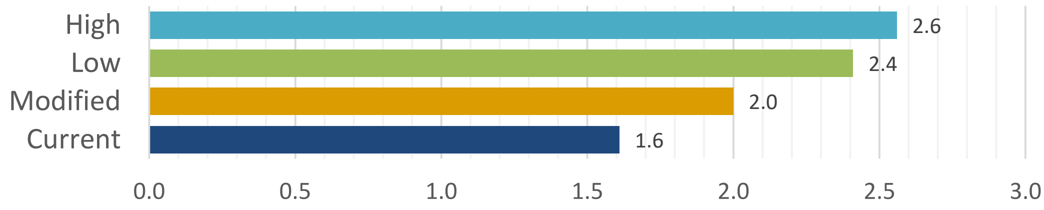

Fig. 3: SPF_{4+} of the SSHP with multiple PVT designs

The improvements in SPF are primarily due to the reduced reliance on direct electric backup heaters, a function of the increased power and energy supplied by the PVT. Figure 4 shows the specific annual thermal energy captured from the PVT array for each design. The baseline system already has relatively high thermal production from the PVT collectors at 485 kWh m^{-2} yr^{-1} due to the low operating temperatures. Production increases by 40% with the heat exchanger modification, and a further 23% with low fan speeds. Here also it can be seen that increasing fan speed has marginal benefits for energy capture, however it could be more critical for peak power.

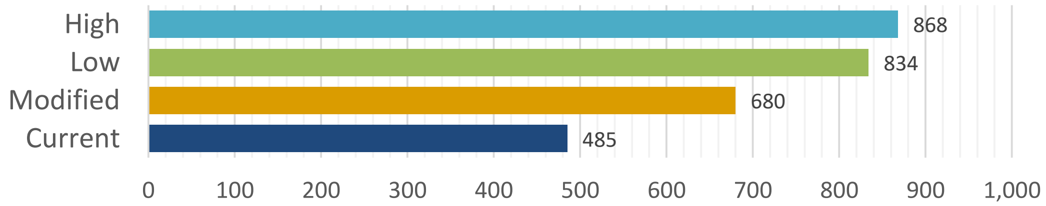

Fig. 4: Specific thermal production (kWh m^{-2} yr^{-1}) of the multiple PVT designs in an SSHP system

SPF values between 1.5 – 3.0 are common for air-to-water heat pumps in a Nordic climate, suggesting a SSHP could be a competitive alternative (Stignor and Walfridson, 2019). The market price for a newly installed ASHP are generally 1150 €/kW (Swedish Refrigeration and Heat Pump Association, 2018) and PV for residential buildings 1300 €/kW (Lindahl et al., 2019), meaning a comparable solution using traditional ASHP would cost approximately €153k. The marginal cost for a PVT system (on top of PV-only) is approximately €60k, making the total cost similar to a GSHP rather than ASHP (Swedish Refrigeration and Heat Pump Association, 2018).

Although not directly comparable on cost with ASHP, PVT provides the potential benefit of little to no fan noise like a GSHP. The main limitation is the low SPF, however it is challenging to say exactly how air or solar sourced heat pumps would perform in an older multifamily house since there are very few examples. There are even modern GSHP installations in Sweden with an SPF_{4+} of 2.7 (Gervind et al., 2016), suggesting that the low values could be a function of high temperature radiators rather than the concept as a whole.

A notable omission from the SSHP results are defrosting losses, which can be as much as 10% in ASHP (Stignor and Walfridson, 2019). Initial experimental results suggest that a PVT sourced system would require much less defrosting due to the solar radiation and if there were no forced convection (Schmidt et al., 2018). Quantification of annual performance and defrosting behavior is certainly needed in future analysis.

5. Conclusions and Future Work

Two applications for PVT integration with heat pumps have been described that have similar or lower investment costs than comparable alternatives while providing additional non-economic value. For GSHP, PVT offers a lower cost alternative to drilling additional boreholes in existing systems, which is likely to be a growing challenge as GSHP markets mature. The target buildings should be those with older heat pumps that are nearing replacement with a more efficient unit, or poorly designed systems that are relying too much on the direct electric backup heater. SSHP may be able to eliminate loud heat exchangers, but they do so at GSHP prices and ASHP performance. SSHP could be viable for customers willing to pay for the increased comfort and technological novelty, however these would likely be traditional "early adopters." More development work is needed to reduce PVT costs if they are to be directly cost competitive with ASHP.

Several companies in Sweden have started to install PVT collectors on degraded boreholes, and while the systems are monitored there lacks enough data to do a full borehole or systems model validation. The difficulty of modeling a complex thermal gradient in a systems tool like TRNSYS means that either more complex modeling and/or improved quality and quantity of monitored systems is needed to validate the preliminary findings here.

As demonstrated with previous studies (Herrando et al., 2019), the increase in PVT heat exchanger area will increase heat transfer rates, suggesting a wetted absorber designs (such as the flax box) should be pursued over additional fin-and-tube development. The addition of forced convection to PVT collectors also shows potential in increasing heat capture from the air in SSHP systems. The target characteristics used here can be guidelines for future design work, however much more detailed modeling is necessary. At the systems level, additional work is needed in the characterization of SSHP systems, for example empirical SPF values, control optimization, and defrosting losses. Since much of the potential for cost reductions rely on high-volume manufacturing processes, feasibility studies in additional climates and markets are also needed to quantify the broader market potential for PVT heat pumps at a European or global level and critical for scalability.

6. Acknowledgements

This study is funded by Mistra Innovation (project no. MI23.1), for which the authors are grateful.

7. References

Bertram, E., Glembin, J., Rockendorf, G., 2012. Unglazed PVT collectors as additional heat source in heat pump systems with borehole heat exchanger. Energy Procedia 30, 414–423. https://doi.org/10.1016/j.egypro.2012.11.049

Chu, J., Cruickshank, C.A., 2014. Solar-Assisted Heat Pump Systems: A Review of Existing Studies and Their Applicability to the Canadian Residential Sector. J. Sol. Energy Eng. 136, 041013. https://doi.org/10.1115/1.4027735

Duffie, J.A., Beckman, W.A., 2013. Solar Engineering of Thermal Processes, Fourth. ed. John Wiley & Sons, Inc., Hoboken, NJ.

EHPA, 2019. European Heat Pump Market and Statistics Report 2019. Brussels.

Emmi, G., Zarrella, A., De Carli, M., Galgaro, A., 2015. An analysis of solar assisted ground source heat pumps in cold climates. Energy Convers. Manag. 106, 660–675. https://doi.org/10.1016/j.enconman.2015.10.016

Eslami-nejad, P., Langlois, A., Chapuis, S., Bernier, M., Faraj, W., 2009. Solar Heat Injection Into Boreholes, in: 4th Canadian Solar Buildings Conference, Toronto, June 25-27, 2009. Toronto, pp. 237–246.

Fossa, M., Minchio, F., 2013. The effect of borefield geometry and ground thermal load profile on hourly thermal response of geothermal heat pump systems. Energy 51, 323–329. https://doi.org/10.1016/j.energy.2012.12.043

Gervind, P., Benson, J., Jardeby, Å., Nordman, R., 2016. Solhybrid och bergvärme- Förnybart med ny systemlösning (2016:01).

Hellström, G., 1989. Duct Ground Heat Storage Model - Manual for Computer Code. Department of

Mathematical Physics, University of Lund, Sweden.

Helpin, V., Kummert, M., Cauret, O., 2011. Experimental and simulation study of hybrid ground source heat pump systems with unglazed solar collectors for french office buildings. Proc. Build. Simul. 2011 12th Conf. Int. Build. Perform. Simul. Assoc. 2957–2964.

Herrando, M., Ramos, A., Zabalza, I., Markides, C.N., 2019. A comprehensive assessment of alternative absorber-exchanger designs for hybrid PVT-water collectors. Appl. Energy 235, 1583–1602. https://doi.org/10.1016/j.apenergy.2018.11.024

Hottel, H.C., Whillier, A., 1955. Evaluation of flat-plate solar collector performance, in: Transcript of the Conference on the Use of Solar Energy, The Scientific Basis, Vol. II, Part 1, Section A. University of Arizona Press, Tucson, Arizona, pp. 74–104.

Klein, S., Beckman, W.A., Mitchell, J., Duffie, J.A., Freeman, T., 2009. TRNSYS 17, A Transient System Simulation Program.

Lindahl, J., Stoltz, C., Oller-Westerberg, A., Berard, J., 2019. National Survey Report of PV Power Applications in Sweden 2018.

Mazzotti, W., Acuña, J., Lazzarotto, A., Palm, B., 2018. Deep Boreholes for Ground-Source Heat Pump - Effsys Expand Final Report.

Pärisch, P., Mercker, O., Oberdorfer, P., Bertram, E., Tepe, R., Rockendorf, G., 2015. Short-term experiments with borehole heat exchangers and model validation in TRNSYS. Renew. Energy 74, 471–477. https://doi.org/10.1016/j.renene.2014.07.052

Pressiani, M., Sommerfeldt, N., Madani, H., 2016. Investigation of PV/Thermal Collector Models for Use With Ground Source Heat Pumps in Transient Simulations, in: Proceedings of the ISES Eurosun 2016 Conference. ISES, Palma de Mallorca, Spain, pp. 1305–1316. https://doi.org/10.18086/eurosun.2016.08.19

Rolando, D., Acuna, J., Fossa, M., 2015. A Web Application for Geothermal Borefield Design. World Geotherm. Congr. 2015 19–25.

Sartori, E., 2006. Convection coefficient equations for forced air flow over flat surfaces. Sol. Energy 80, 1063–1071. https://doi.org/10.1016/j.solener.2005.11.001

Schmidt, C., Schäfer, A., Kramer, K., 2018. Single source "solar thermal" heat pump for residential heat supply: Performance with an array of unglazed PVT collectors, in: 12th ISES Eurosun Conference. Rapperswil, Switzerland.

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. Sol. Energy 190, 44–62. https://doi.org/10.1016/J.SOLENER.2019.07.080

Sommerfeldt, N., Madani, H., 2016. Review of Solar PV/Thermal Plus Ground Source Heat Pump Systems for European Multi-Family Houses, in: 11th ISES Eurosun Conference. Palma de Mallorca, Spain, pp. 1382–1393. https://doi.org/10.18086/eurosun.2016.08.15

Sommerfeldt, N., Ollas, P., 2017. Reverse Engineering Prototype Solar PV / Thermal Collector Properties from Empirical Data for Use in TRNSYS Type 560, in: Proc. of the ISES Solar World Congress 2017. ISES, Abu Dhabi, pp. 1121–1132. https://doi.org/10.18086/swc.2017.18.11

Spitler, J., Cullin, J., Bernier, M., Kummert, M., Cui, P., Liu, X., Lee, E., Fisher, D., 2009. Preliminary intermodel comparison of ground heat exchanger simulation models, in: Proceedings of 11th International Conference on Thermal Energy Storage. Stockholm, Sweden.

Stignor, C.H., Walfridson, T., 2019. Nordsyn study on air-to-water heat pumps in humid Nordic climate (TemaNord 2019:502). https://doi.org/10.6027/TN2019-502

Swedish Refrigeration and Heat Pump Association, 2018. PULSEN 2018 - The industry more positive than ever! [WWW Document]. URL https://skvp.se/aktuellt-o-opinion/statistik/pulsen/2018-eng (accessed 6.1.18).

Thür, A., Giovannetti, F., Fischer, S., 2018. Improvements Developed during the IEA SHC Task 54 [WWW Document]. URL http://task54.iea-shc.org/Data/Sites/1/publications/ISEC-2018-Presentation-Task54-Thuer.pdf (accessed 10.30.18).

Weiss, W., Spörk-Dür, M., 2019. Solar Heat Worldwide. IEA Solar Heating and Cooling Programme.