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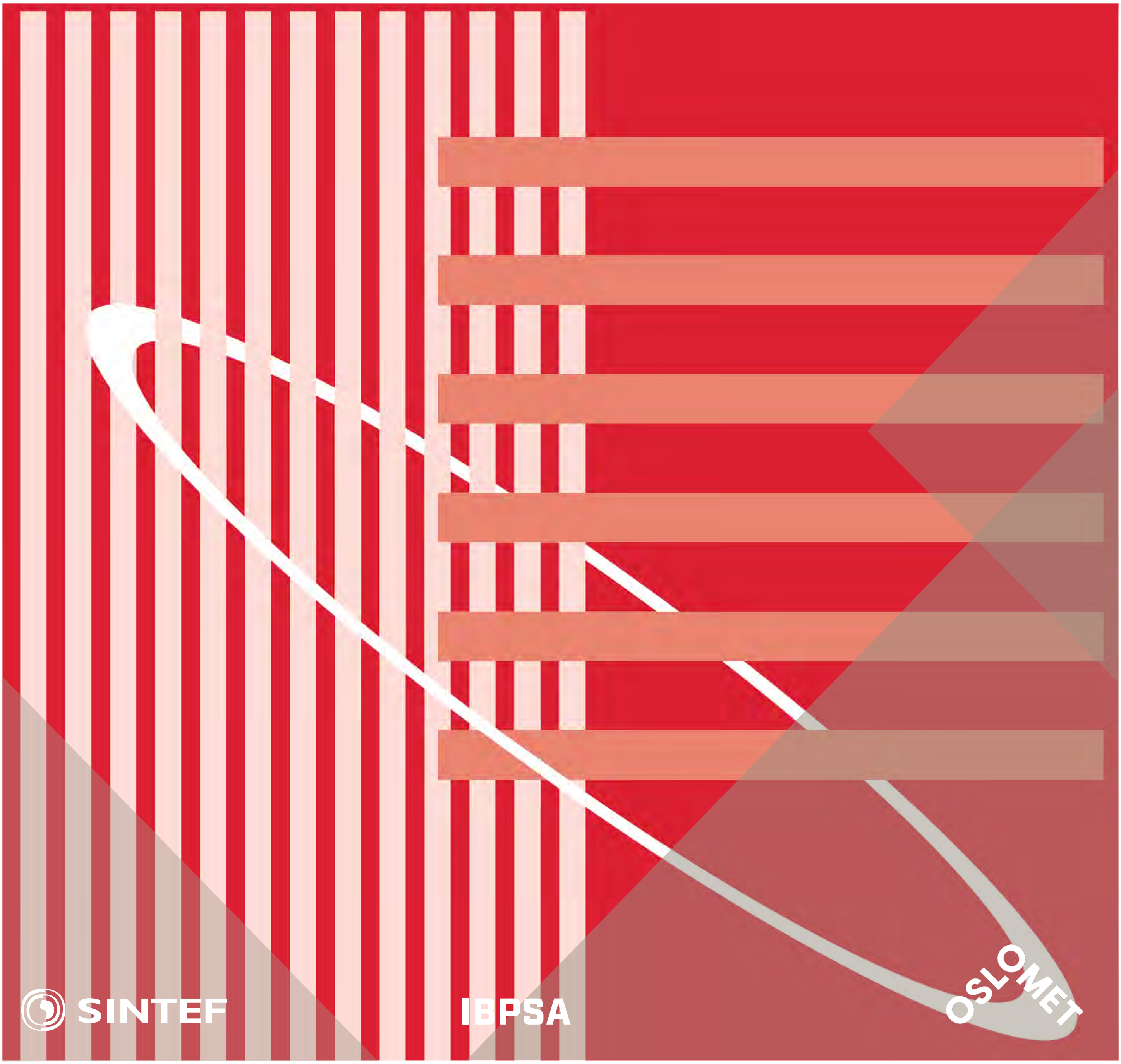

SINTEF Proceedings

Editors:
Laurent Georges, Matthias Haase, Vojislav Novakovic and Peter G. Schild

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Solar PVT for heat pumps: Collector development, systems integration, and market potential

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Abstract

Solar PV/thermal hybrid collectors have been researched for decades, but have never had market success. This paper motivates a research agenda for PVT based on heat pump integration. The market potential is defined and prior research reviewed with an emphasis on systems and collector modelling methods. The result is a research project that works on the component and systems level, with digital and physical prototypes. This project is expected to deliver validated evidence on the advantages of PVT as a compliment to ground source heat pumps and an alternative to air source heat pumps, which can contribute to the decarbonisation of buildings in Europe.

Introduction

Building electrification with heat pumps is a promising technique for heating decarbonisation, particularly if combined with solar energy. Historically, solar heat pump (SHP) research has focused on solar thermal technologies (Poppi et al., 2018), however cost reductions in photovoltaics (PV) has led to an increase in PV based SHP research and a renewed interest in PV-thermal (PVT) hybrid collectors (IEA, 2018). PV installations are increasing rapidly, but PVT has struggled to find success in the market due to issues of reliability, lack of certification standards, confusing range of designs and applications, and high cost relative to alternative pool or domestic hot water (DHW) heating approaches (Good et al., 2015).

PVT collectors combine PV and solar thermal (ST) designs to generate electricity and heat from the same module. Traditionally this meant adding PV cells to the front surface of a glazed ST collector, but more recently manufacturers have been adding heat exchangers to the rear side of traditionally manufactured PV modules.

The application of PVT on the source side of a heat pump offers multiple benefits – the heat pump can receive higher source temperatures for more efficient operation, the lower operating temperature of the collector increases thermal efficiency, and the cooler PV will generate more electricity. However, there are limits to the net energetic benefits a solar collector can have as a heat pump source (Haller and Frank, 2011) and it has been suggested that solar heat should be used for higher-temperature, DHW applications first and heat pump sources second (Kjellsson et al., 2010). This approach assumes that the solar collector should be readily available to prepare DHW, which requires a specific design strategy that is inconsistent with the design of a collector used as a heat pump source – namely, the use of glazing and insulation.

While striving for cost reductions and increased reliability, most PVT collectors on the market today do not use isolative glazing, only glass in contact with the PV cells that protects them from damage (Weiss and Spörk-Dür, 2019). This makes them less thermally efficient than glazed collectors for DHW preparation, but rear-side insulation still makes it possible to reach DHW temperatures, particularly in warmer climates. When operating at the low temperatures used in a heat pump supply circuit (-10° to +20° C), which are often at or below ambient air, the insulation becomes a barrier to efficiency by hindering heat transfer from the air. So in the interest of reducing costs and increasing efficiency, this line of research focuses exclusively on the design of PVT collectors for source side integration of heat pumps.

The objective of this paper is to motivate and describe a research plan for developing a novel, low-cost PVT collector specifically for use in a range of SHP systems. This is achieved by defining specific markets and applications where PVT-SHP can provide more value than alternative solutions, describing the most promising methods of systems integration matched to specific applications, and identifying specific design strategies for PVT collectors for future development. For each stage of the development, appropriate simulation tools are identified, motivated, and described.

This paper is an amalgamation of insights learned over multiple studies performed by the authors during a four year period, and space limitations prevent a complete reporting of model details. References to papers with complete details are provided and the topics presented here are selected to highlight the modelling process and their application towards future development of SHPs.

Applications and market potential

The demand for heat pumping machines is growing in Europe (EHPA, 2019). There are many styles based on heat source, sink, and application, but in buildings it is most common to see heat pumps in single family houses (SFH) with air-to-air or air-to-water configurations. In larger buildings and/or in colder climates, brine-to-water ground source heat pumps (GSHP) become more common for their improved efficiency over air source heat pumps (AHSP).

SHP designs are extremely diverse and multiple reviews have found that no technical or economically optimal configurations have been found (Chu and Cruickshank, 2014; Mohanraj et al., 2018a; Poppi et al., 2018). Compared to technical aspects, much less attention has been paid to the economic considerations of SHP and their market potential to impact global energy challenges. This study is limited to liquid based PVT collectors integrated with air-to-water and GSHP, which share some common design strategies but utilize different heat sources. PVT can be designed with air as a working fluid in conjunction with an air-to-air heat pump, but the design strategy is considerably different from the liquid based design.

Ground source heat pumps

GSHP rely on the ground's mass to maintain higher temperatures during heating seasons. When the majority or entirety of a load is for heating, the volume of soil/rock surrounding the heat exchanger reduces in temperature. This is usually designed into the system to maintain acceptable performance during its lifetime, however problems can arise if a heat exchanger is undersized.

The primary consequence of undersized ground heat exchangers (GHE) is a reduction in heat pump efficiency resulting in higher electricity use. It can also lead to greater reliance on the direct electric backup heater, which is much more detrimental to efficiency. It is also possible for water inside and around the heat exchanger to freeze, causing frost heaves and damaging the ground at the surface, or potentially damaging the heat exchanger.

Undersized GHEs are not currently a systemic problem, however the issue is growing in more mature markets like Austria, Sweden, and Switzerland. After two to three decades of installations, many buildings will be ready to retrofit a new, more efficient heat pump. The higher efficiency combined with the already degraded ground temperatures means the GHE will be undersized. One solution is to increase the size of the GHE, if the area permits, however this just delays the problem.

PVT can provide benefits in two ways: as a secondary thermal energy source to the heat pump, thereby reducing the load on the ground, and by regenerating the ground with excess solar energy in the summer months. This not only solves the immediate undersizing problem, but will stabilize the GHE temperatures indefinitely. Connecting the PVT in series with the ground, as shown in Figure 1, makes integration with existing systems simple and scalable. It does not require changes to the storage tanks like traditional solar thermal systems, and few if any modifications to the heat pump are required.

Based on installation rates during the 2010's, in 10-15 years most countries in Europe will be routinely upgrading heat pumps leading to an increased potential for undersized GHEs. With approximately 100,000 GSHP sold each year, this is a smaller but notable market segment that can contribute to PVT's scalable commercialization.

The higher investment cost for GSHP make them suitable for larger multi-family residential or commercial buildings, which are often lacking the land area needed for large GHEs. ASHP alternatives are often unacceptably noisy, leaving a significant part of the building stock inaccessible to heat pumps and electrification. Series connected solar collector simulations have demonstrated the potential for GHE reductions (Bertram et al., 2012; Eslami-nejad et al., 2009; Reda and Laitinen, 2015). PVT in particular has been shown to reduce area requirements by over 80% and remain economically competitive with alternative heating sources (Sommerfeldt and Madani, 2019). Considering over half of the residential building stock in Europe consist of multi-family houses (MFH) (Eurostat, 2015) plus the potential for commercial buildings, PVT could help unlock a large, underserved market for GSHP. This is particularly relevant given the challenges of decarbonizing heat supply in urban building stocks.

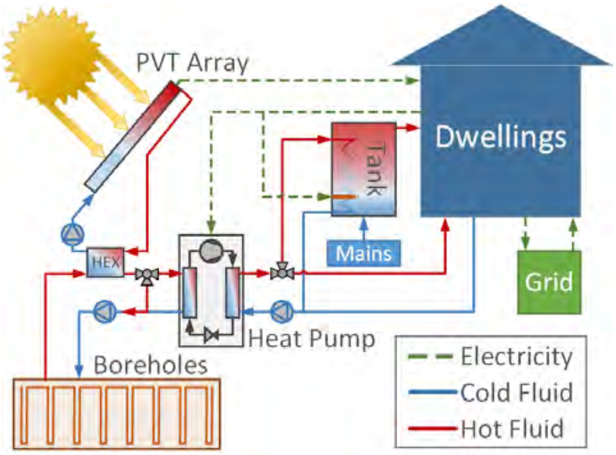

Figure 1: GSHP with series connected PVT

Solar source heat pumps

ASHP make up over 90% of the European heat pump market, with about 45% being air-to-water (EHPA, 2019). One of the main drawbacks to ASHP are disturbances from loud fans in the outdoor heat exchangers. Many SFH have 3-5 kW of PV capacity, corresponding to 20-30 m^2, which would provide a notably larger surface area for an ASHP heat exchanger than the typical fin-and-tube units. With a larger surface area, the need for forced convection is reduced and potentially eliminated, thereby solving the noise problem with ASHP. Even if fans cannot be eliminated, placing them on the roof behind the PVT collectors will help reduce their impact at ground level.

Solar source heat pumps are most often researched as direct expansion systems, where the PVT replaces the evaporator and uses refrigerant as the working fluid, however the most successful systems have relied on refrigerants with high global warming potential (Mohanraj et al., 2018b). There are natural refrigerants with good performance, however they are flammable and/or require heavy modification to the system. Additionally, most research has been performed in subtropical climates, limiting broader market appeal (Chu and Cruickshank, 2014).

An indirect design, shown in Figure 2, uses a secondary fluid (i.e. a water/glycol mixture) to transfer heat from the PVT to the evaporator inside the heat pump. While the heat exchanger can introduce cost and performance penalties, this approach is more flexible and generalizable for scaling up across multiple markets. It also relies on familiar technologies and approaches within the solar system components, reducing needs for installer training.

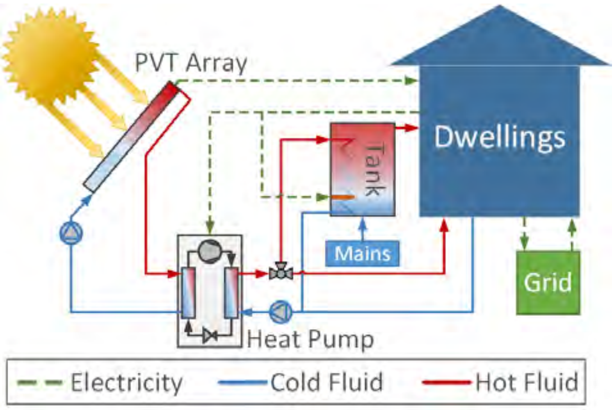

Figure 2: PVT sourced heat pump

Over 500,000 ASHP were sold in Europe in 2018, double the quantity sold in 2012 with expectations for continued growth (EHPA, 2019). After a boom/bust cycle during the 2000's and early 2010's, the solar PV market in Europe is growing again with most systems installed in buildings (IEA, 2019). Combining these two trends gives PVT a larger market to grow with potential to deliver an improved product over ASHP. The performance of a PVT sourced heat pump for Europe is still not well known. A recent laboratory study demonstrated the potential for insulated PVT collectors to meet peak winter loads in a German climate, concluding that the system concept showed promise but should use uninsulated collectors (Schmidt et al., 2018). Even less understood is the economic performance and potential for improvement, however the market potential and scale for a heat pump specific PVT is motivation for further development.

Systems integration and modelling

SHPs are predominantly simulated using quasi-steady state systems modelling tools, such as Matlab/Simulink, Polysun, and TRNSYS. These tools are considered to have an ideal balance between detail, accuracy, and computational resources while also having the flexibility for novel system design. This chapter presents the process of building a complete PVT plus GSHP model in TRNSYS, the auxiliary models used to complete the boundary conditions, and a sampling of results with comparisons. A more thorough description of the study can be found in (Sommerfeldt and Madani, 2019).

Model description

TRNSYS is particularly popular for SHP systems due to the flexibility of design using well-developed libraries of solar and heating system components. A complete systems model is simulated including the building envelope, eight-zone space heating distribution, domestic hot water tanks, heat pump, boreholes, PVT collectors, and auxiliary pumps. The model's goal is to quantify the technical and economic potential for reducing borehole field size when combined with a PVT array in series. This is measured using seasonal performance factor (SPF) considering all auxiliary devices (e.g. pumps) necessary for the function of the complete system, and a 20 year total life cycle cost (TLCC) that includes the residual value of the PVT and boreholes which are assumed to last 30 and 60 years, respectively.

The simulation is run for 20 years, which corresponds to typical heat pump lifetimes and captures long-term temperature changes in the ground due to heat extraction and injection. A three minute time step is used to capture the detailed control response of the heat pump and self-consumption of PV generation. Self-consumption can be reported as 5-10% higher when using a typical 60 minute time step (Cao and Sirén, 2014). One minute time steps are technically possible using the tools presented here, however three minutes was assumed to be a reasonable compromise for processing time. One 20 year simulation requires approximately 3.5 hours on an Intel i7-7600 running at 2.9 GHz.

The target building is a 1980's construction, 2000 m^2 MFH located in Stockholm, Sweden. Weather data representing a typical meteorological year between 1991 and 2010 is generated using Meteonorm 7.2. Atmospheric conditions (e.g. temperature, relative humidity) are generated hourly and linearly interpolated for the three minute time steps, but solar radiation is simulated using one minute time steps using the stochastic Hofmann model (Hofmann et al., 2014) and averaged across three minutes. The resulting space heating demand is 125 $kWh/m^2/yr$.

Electricity and hot water demand inside the building is generated at one minute intervals using a Markov Chain behavioural model (Widén and Wäckelgård, 2010) and averaged to three minutes. Electrical loads are imposed as an 80/20 split of radiative and convective internal gains and the hot water loads are served by two, fully mixed 1000 l tanks. Specific annual demand for DHW and electric appliances are 30 $kWh/m^2/yr$ and 38 $kWh/m^2/yr$ respectively.

The heat pump is modelled with a black box approach, using a three-dimensional interpolation based on the performance map of a commercially available, 52 kW (nominal) heat pump. The model accepts source temperature, supply temperature, and compressor speed, and returns compressor electricity demand and thermal output. This is a common technique in heat pump systems modelling (Haller et al., 2012; Madani et al., 2011) as it dramatically reduces the computational needs of a detailed theoretical heat pump model, however it does require empirical data. The compressor speed is PID controlled using a heating supply temperature curve. Auxiliary heaters in the DHW tanks and in series with the heat pump are used to provide supplementary heat in cases where the boreholes are severely undersized. While an auxiliary heater would not normally be used this way in a capacity controlled heat pump installation, this approach directly captures the energetic penalty of not meeting heating comfort demands as opposed to the indoor temperature penalty method.

The baseline borehole field is sized according to a modified ASHRAE method implemented in the web-based GeoDesigner (Rolando et al., 2015) using hourly space and DHW demands from the building model. The result is a field consisting of 12 boreholes with single U-tubes in a 3x4 pattern, 300m deep and 20m spacing. The borehole field is modelled in TRNSYS using Type557a, based on the validated duct storage model (Hellström, 1989). This model is nearly ubiquitous in TRNSYS studies in large part due to being readily available in the pre-packaged libraries and acceptable long-term response. However the short term response has been criticised with alternative models being proposed (De Rosa et al., 2015; Godefroy, 2014), but a workaround proposed by Pärisch et al. (2015) is used here and only relies simple pipe models. Besides accessibility, another benefit of using Type557 is the ease of parametric analysis on length and spacing as compared to a g-function based model.

The system includes a prototype PVT collector being developed specifically for heat pump integration. Empirically derived coefficient models (like the heat pump model) are common but unavailable here due to the developmental nature of the PVT. Therefore a theoretical model is used based on the traditional fin-and-tube design and validated with a detailed finite-volume numerical model and measured performance. Details of the PVT model are presented in the next chapter.

Results

In the full paper, a parametric analysis of borehole length and spacing is considered to quantify the potential reductions due to PVT (Sommerfeldt and Madani, 2019). For brevity, a sample of results are presented, focusing on undersized BHE. The impact of shortened boreholes and various PVT areas on the 20-year average SPF is shown in Figure 3 and TLCC in Figure 4. The borehole (BH) length and PVT area are presented in specific units based on total annual heat demand of the building (326 MWh/yr) to be more generalizable, but for this case the markers represent discrete cases where the farthest right case is the default 12 borehole field (total length 3600 m) and two boreholes (equivalent to 600 m) are removed for each point to the left. The largest PVT array is assumed to fill the entire roof, consisting of 144 collectors equivalent to 234 m^2 and 40 kW$_p$ of PV capacity.

When PVT is added to an adequately sized borehole field, the improvement in SPF is at most 3%. For a system with equivalent performance to the baseline, up to 18% of the total borehole length can be reduced and if a 3% decrease in SPF is acceptable the borehole length can be reduced by up to 33%. These results are comparable to previous studies on PVT plus GSHP simulations in Germany (Bertram et al., 2012) and Canada (Brischoux and Bernier, 2016). For a total borehole length reduced by more than 33% reduction, backup heater usage increases, rapidly degrades SPF, and borehole freezing (indicated by white markers) becomes a potential risk.

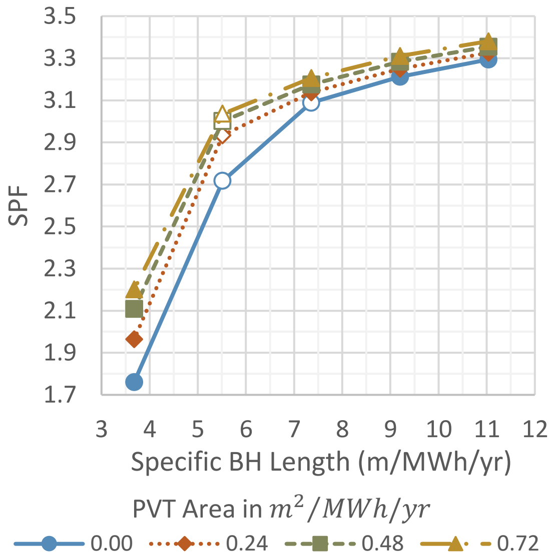

Figure 3: SPF as a function of PVT area and BH length

The TLCC results in Figure 4 suggest that the additional costs for PVT are greater than the savings from reduced borehole length. In the least cost PVT case that avoids borehole freezing (7.3 m/MWh/yr, 0.24 m^2/MWh/yr) the lifetime cost is 4% higher than baseline with a 5% decrease in SPF. For a complex systems model considering long-term economics, this is within reasonable uncertainty.

These results are also highly dependent on Swedish market conditions characterized by low electricity and drilling prices. Low electricity prices reduce the motivation for efficiency and low borehole prices reduce the economic benefits shortened length. Drilling/borehole prices are particularly critical – it is assumed here that boreholes cost approximately €32/m to install, whereas up to €100/m have been used in other European markets (Helpin et al., 2011). For this system, a doubling of borehole cost would make all PVT solutions economically competitive, suggesting the concept will provide greater value to markets outside of Sweden, however comparisons with ASHP and alternative heating sources are needed.

When compared to district heating, which over 90% of Swedish MFH use, GSHP can reduce cost and emissions, however most do not have the requisite land area for boreholes. PVT can reduce the area needs by over 80% through length and spacing reductions, thereby increasing market potential (Sommerfeldt and Madani, 2019).

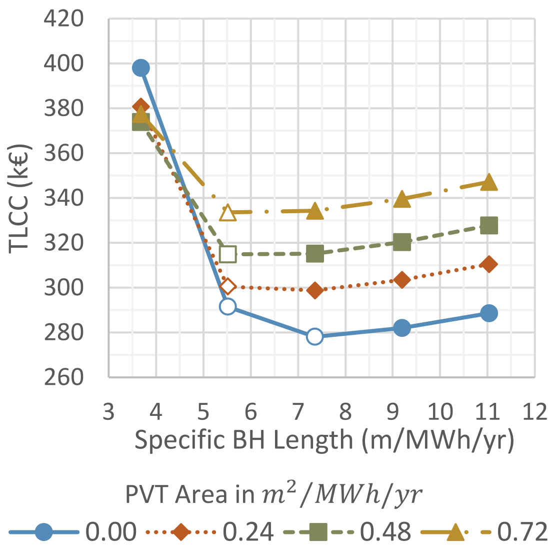

Figure 4:TLCC as a function of PVT area and BH length

Future research

The results presented here in conjunction with the full paper, demonstrate digitally that there is an opportunity for greater GSHP adoption with PVT integration. There are several disparate modelling tools and component models, all of which have been validated, that combine into a single systems model. A challenge with many systems simulation studies is the limited opportunity to test novel concepts in real world applications for full systems validation. Given the risk to system damage from a significantly undersized borehole field, proving this concept in a monitored demonstration is critical to broader market acceptance. The validated model and pilot site would also contribute to further optimization at both the component and system levels.

Broader acceptance will also require expanding simulations to cover additional markets outside of Sweden, and additional applications beyond new systems. For example, the heat pump replacement market described above, which requires the development of a temperature degraded borehole model. The complete systems model presented here is capable of simulating these boundary conditions, however validating them is a crucial next step. High quality, long-term borehole field measurements are rare, however there are opportunities in building demonstration projects that rely on existing, degraded boreholes for validation.

Collector development

This section presents a new review on the design principles of PVT collectors and the recommended features for SHP applications. Model validation is a critical part of prototype development, therefore a brief model description and validation is also presented, with full details available in (Sommerfeldt and Ollas, 2017).

Design principles

For much of the history of PVT design, PV cells were laminated to a typical solar thermal collector as a method for increasing total efficiency (Zondag, 2008). However, the prices for PV modules have dropped dramatically in the last decade due to manufacturing scale and standardization, making it more interesting to flip the design by adding heat exchangers to PV modules. This is typically done by bonding the heat exchanger to the rear side of a PV module using thermo-conductive paste (Aste et al., 2014) or mechanically pressing it into contact and applying a thermo-conducting grease.

Solar thermal absorbers are most commonly built from aluminium and/or copper for their high conductivity and strength. The sheet-and-tube design is most common, however roll-bonded and box-channel designs are potential alternatives (Aste et al., 2014). Sheet-and-tube relies on the absorber to conduct heat to the tubes carrying working fluid, however the small contact surface and imperfect bonding between the tubes and plate hinders heat transfer (Aste et al., 2014). Roll-bonding creates channels between two aluminium sheets that can be formed in nearly any shape, enabling greater surface area contact for the fluid but with higher pressure drops and cost (Bombarda et al., 2016). The box-channel design relies on extrusion, creates the highest surface area contact of the three designs, and can use metallic or polymeric materials (Zondag, 2008).

The performance differences between each design have been tested in several studies, showing that the greater surface area of roll-bond and box-channel absorbers achieve higher efficiencies than sheet-and-tube (Bombarda et al., 2016; Herrando et al., 2019; Kim and Kim, 2012). The gains in surface area can even be enough to overcome lower thermal conductivity of polymers (Herrando et al., 2019).

The use of polymers for solar thermal collectors has been hindered by high temperatures, which lead to rapid degradation of the material. In the case of heat pump integration, the low temperatures can reduce cost in both the PVT collector and the connective piping. Using a box-channel design, polycarbonate has the potential to reduce cost by 22% over a traditional absorber (Herrando et al., 2019). There is also no need for insulation since gains from the ambient air are desired, further reducing costs.

Modelling approach

PVT models are an extension of solar thermal models, which can be categorized by dimension (1D, 2D, 3D) and method (analytical, numerical). The trade-offs are largely between accuracy and computational effort. Zondag et al. (2002), found that in the calculation of daily yield, the error that comes from using a 1D steady-state versus a 3D numerical model is 0.2%. However, Chow (2003) suggests that PVT performance is transient in nature and requires a dynamic model for fluctuating ambient conditions and detailed control strategies. This is largely an issue of the model being fit for purpose, where detailed heat exchanger design benefits from 3D numerical models, which are the most computationally expensive, and can then be translated into faster 1D/2D analytical models for use in systems analysis.

As demonstrated in the previous chapter, TRNSYS is a powerful tool for complex systems analysis, such as solar heat pumps. Type 560 is a 2D, theoretical PVT model based on the Hottel and Whillier thermal model, later modified by Florschuetz to incorporate PV (Florschuetz, 1979) and is available in the TRNSYS extended library. Being theoretical, the boundary conditions must be validated when working with untested PVT prototypes, as is the case in this study. The goal is to determine the one critical variable that is unavailable via specification sheets and difficult to estimate; thermal resistance between the PV cells and rear side heat exchanger.

Outdoor testing was to provide the necessary empirical data to validate the model, however late in the test cycle, an airlock was discovered with an IR camera, shown in Figure 5**Error! Reference source not found.**, which restricted fluid flow in the left collector. Since Type 560 requires the flow in all runners to be equal, this led to the use of TAITherm, a commercial heat transfer solver that uses a numerical, finite volume approach and allows for individual control of flow in the heat exchanger pipes.

Figure 5: IR image taken during testing

TAITherm uses a 2.5D numerical model using a finite-volume approach. An image of the TAITherm model is shown in Figure 6, which relies on plate and tube surface geometry with assigned thicknesses, connected by 1D conductivity links, and 1D fluid flow model in the tubes to generate convection coefficients. There are two plates in the model; one to represent the PV module with all its layers of glass, silicon, and polymers, and a second to represent the aluminium heat exchanger plate. The plates and tube are thermally linked via a 1D conductivity model and both the front and back surfaces are connected to ambient air nodes with a convection coefficient.

The model is constructed using the known physical geometry and 5-minute measured boundary conditions from the test (i.e. weather and fluid properties). It's tuned considering the flow in each pipe, thermal conductivity between the PV and heat exchanger, and the rear side convection coefficient. The outlet temperature of the heat transfer fluid is used as the primary calibration measurement and the thermal power output is used as a secondary indicator. Thermal power is calculated using measured volumetric flow rate, fluid density, and inlet temperature with modelled outlet temperature. The validation is measured with mean absolute error (MAE) and the correlation of the outlet temperature and thermal power time series, as well as the differences in total thermal energy generated over the test periods.

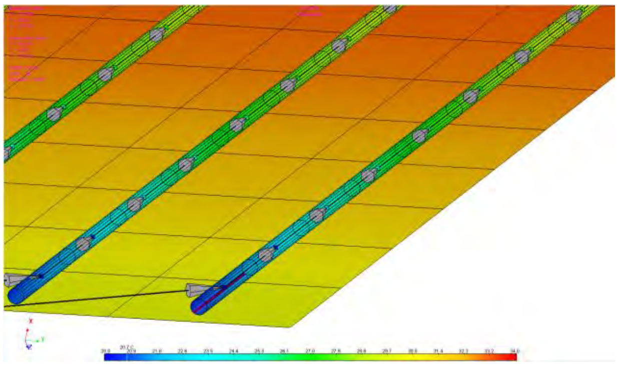

Figure 6: Detailed view of TAITherm model geometry

The surface temperatures in Figure 5**Error! Reference source not found.** are compared with those in the TAITherm model to find that 99%, or effectively all, of the working fluid is passing through the right collector with an insignificant flow through one runner on the left. This made it possible to validate Type 560 directly using the empirical data and test the differences between it and TAITherm. All of the same geometry and climate boundary conditions are applied to Type 560, and tuning performed in an identical manner as TAITherm aside from pipe flow.

Results

The time series results for thermal and electrical energy production are shown in Figure 7. It can be seen that the TAITherm model tracks the measured data more consistently than Type 560, with less pronounced peak and valleys during variable irradiation events. This is confirmed by a lower MAE and higher correlation, and is likely due to the inclusion of the thermal mass, which is missing in Type 560. Mass can be added to Type 560 by using auxiliary models (e.g. pipes) that damp thermal response at the system level, but not at the collector.

The final thermal resistance values range from 0.005 to 0.010 m^2KW^{-1} in TAITherm and 0.010 to 0.040 m^2KW^{-1} in Type 560. Chow describes the thermal resistance between the PV cells and absorbers as being perfect when equal to 0.0001 m^2KW^{-1}, and defective at 0.040 m^2KW^{-1} (Chow, 2003). Given that the heat exchanger is mechanically pressed to the PV module, the high resistance values are not unexpected, but motivate the need for improved design and manufacturing that can improve conductivity while still reducing cost.

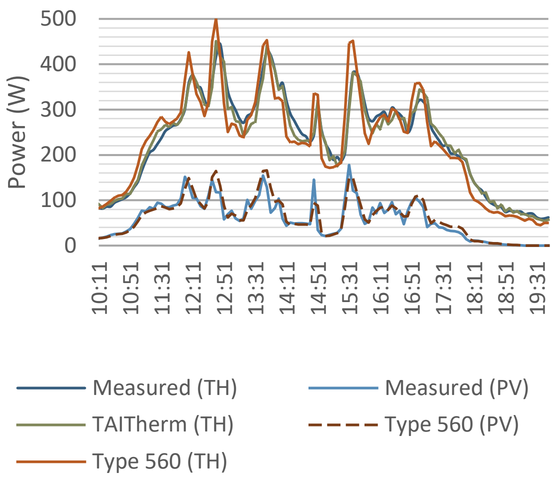

Figure 7: PVT energy production time series

Future research

There has been an increase in PVT research in recent years, primarily boosted by the IEA SHC Task 60. Nevertheless, the PVT heat pump concept is relatively undeveloped and thus has had little design dedicated to PVT collectors as part of a heat pump system. Therefore, there is an opportunity for the development of a novel collector design aimed at maximizing the heat transfer area between absorber and coolant, considering the cost reductions in the materials and manufacturing process afforded by heat pump integration. This can be achieved by developing a 3D numerical models paired with computational fluid dynamics (CFD) to identify optimal flow distribution patterns and heat flux potential. This model can then be transferred over to an analytical model in TRNSYS for rapid computation within a larger, heat pump systems analysis.

Conclusions

This paper set out to motivate and describe research needs for the development of a novel, low-cost PVT collector specifically for use in SHP systems. The rapid growth of the heat pump and PV markets worldwide indicate that there is a growing opportunity for PVT to finally scale up from a niche product to widespread adoption. The systems and PVT modelling methods presented here offers a glimpse into the simulation techniques needed to deliver holistic digital prototypes.

Future work

A new research project started in spring 2020 aims to further the development of PVT heat pumps using the techniques describe here. 3D numerical PVT collector models will be digitally prototyped in COMSOL, leading to physical prototypes validated in an outdoor laboratory. The core goals of the design is to improve conductivity with PV, enhance heat capture from the air, and reduce material and manufacturing costs. Likewise, the new prototypes will be transferred to TRNSYS for systems modelling, where novel configurations and controls will be simulated for multiple markets across Europe. These models will be validated via a MFH pilot system as well as a lab-scale system installed outdoors.

This research agenda can deliver techno-economically optimized and validated PVT based heat pump system designs for multiple buildings, configurations, and markets around Europe. The results can help build installer and consumer confidence in the concept and contribute towards the continued increase of renewable energy and decarbonisation goals in buildings and cities.

Acknowledgement

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References

Aste, N., del Pero, C., Leonforte, F. (2014). Water flat plate PV-thermal collectors: A review. *Sol. Energy 102*, 98–115.

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.

Bombarda, P., Di Marcoberardino, G., Lucchini, A., Leva, S., Manzolini, G., Molinaroli, L., Pedranzini, F., Simonetti, R. (2016). Thermal and electric performances of roll-bond flat plate applied to conventional PV modules for heat recovery. *Appl. Therm. Eng. 105*, 304–313.

Brischoux, P., Bernier, M., 2016. Coupling PV/T Collectors with a Ground-Source Heat Pump System in a Double U-tube Borehole, in: *2016 ASHRAE Winter Conference*. ASHRAE, Orlando, Florida, p. OR-16-C046.

Cao, S., Sirén, K. (2014). Impact of simulation time-resolution on the matching of PV production and household electric demand. *Appl. Energy 128*, 192–208.

Chow, T.T. (2003). Performance analysis of photovoltaic-thermal collector by explicit dynamic model. *Sol. Energy 75*, 143–152.

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.

De Rosa, M., Ruiz-Calvo, F., Corberán, J.M., Montagud, C., Tagliafico, L.A. (2015). A novel TRNSYS type for short-term borehole heat exchanger simulation: B2G model. *Energy Convers. Manag. 100*, 347–357.

EHPA (2019). European Heat Pump Market and Statistics Report 2019. Brussels.

Eslami-nejad, P., Langlois, A., Chapuis, S., Bernier, M., Faraj, W., 2009. Solar Heat Injection Into Boreholes, in: *4th Canadian Solar Buildings Conference*, Toronto (Canada), June 25-27, 2009.

Eurostat (2015). Housing Statistics [WWW Document]. http://ec.europa.eu/eurostat/statisticsexplained/index.php/Housing_statistics#Further_Eurostat_information (accessed 9.12.16).

Florschuetz, L.W. (1979). Extension of the Hottel-Whillier model to the analysis of combined photovoltaic/thermal flat plate collectors. *Sol. Energy 22*, 361–366.

Godefroy, V. (2014). Élaboration Et Validation D'Une Suite Évolutive De Modèles D'Échangeurs Géothermiques Verticaux. PhD Thesis.

Good, C., Chen, J., Dai, Y., Hestnes, A.G. (2015). Hybrid Photovoltaic-thermal Systems in Buildings – A Review. Energy Procedia 70, 683–690.

Haller, M.Y., Bertram, E., Dott, R., Afjei, T., Ochs, F., Hadorn, J.-C. (2012). Review of Component Models for the Simulation of Combined Solar and Heat Pump Heating Systems. *Energy Procedia 30*, 611–622.

Haller, M.Y., Frank, E. (2011). On the potential of using heat from solar thermal collectors for heat pump evaporators, in: *ISES Solar World Congress*. Kassel, Germany.

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.

Hofmann, M., Riechelmann, S., Crisosto, C., Mubarak, R., Seckmeyer, G. (2014). Improved synthesis of global irradiance with one-minute resolution for PV system simulations. *Int. J. Photoenergy 2014*.

IEA (2019). Trends in photovoltaic applications 2019 (T1-36:2019).

IEA (2018). Solar Heating and Cooling Task 60 - PVT Systems: Application of PVT Collectors and New Solutions in HVAC Systems.

Kim, J.H., Kim, J.T. (2012). The experimental performance of an unglazed PVT collector with two different absorber types. *Int. J. Photoenergy 2012*.

Kjellsson, E., Hellström, G., Perers, B. (2010). Optimization of systems with the combination of ground-source heat pump and solar collectors in dwellings. *Energy 35*, 2667–2673.

Madani, H., Claesson, J., Lundqvist, P. (2011). Capacity control in ground source heat pump systems: Part I: Modeling and simulation. *Int. J. Refrig. 34*, 1338–1347.

Mohanraj, M., Belyayev, Y., Jayaraj, S., Kaltayev, A. (2018a). Research and developments on solar assisted compression heat pump systems – A comprehensive review (Part-B: Applications). *Renew. Sustain. Energy Rev. 83*, 124–155.

Mohanraj, M., Belyayev, Y., Jayaraj, S., Kaltayev, A. (2018b). Research and developments on solar assisted compression heat pump systems – A comprehensive review (Part-A: Modeling and modifications). *Renew. Sustain. Energy Rev. 83*, 124–155.

Nasrin, R., Hasanuzzaman, M., Rahim, N.A. (2018). Effect of high irradiation and cooling on power, energy and performance of a PVT system. *Renew. Energy 116*, 552–569.

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.

Poppi, S., Sommerfeldt, N., Bales, C., Madani, H., Lundqvist, P. (2018). Techno-economic review of solar heat pump systems for residential heating applications. *Renew. Sustain. Energy Rev. 81*, 22–32.

Reda, F., Laitinen, A. (2015). Different strategies for long term performance of SAGSHP to match residential energy requirements in a cold climate. *Energy Build. 86*, 557–572.

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

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.

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.

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

Widén, J., Wäckelgård, E. (2010). A high-resolution stochastic model of domestic activity patterns and electricity demand. *Appl. Energy 87*, 1880–1892.

Zondag, H. (2008). Flat-plate PV-Thermal collectors and systems: A review. *Renew. Sustain. Energy Rev. 12*, 891–959.

Zondag, H. a., de Vries, D.W., van Helden, W.G.J., van Zolingen, R.J.C., van Steenhoven, a. a. (2002). The thermal and electrical yield of a PV-thermal collector. *Sol. Energy 72*, 113–128.