effsys EXPAND

Resurseffektiva kyl- och värmepumpssystem
samt kyl- och värmelager

Ground Source Heat Pumps for Swedish Multi-Family Houses

Innovative Co-Generation and Thermal Storage Strategies

Nelson Sommerfeldt & Hatef Madani

June 2018

Energimyndigheten

Foreword

The authors would like to thank the Swedish Energy Agency and Effsys Expand board for funding this research. A large thank you goes also to the industrial partners who participated in and supported the project:

- Thermia Värmepumpar
- Skånksa Energilösningar
- Solhybrid i Småland
- Bengt Dahlgren
- Avanti System
- Nowab
- BRF Moranviken

Thanks also goes to Davide Rolando at KTH for all the providing valuable input on borehole modeling and all of the TRNSYS discussions. We also appreciate all of the work done by the master's students in courses and theses that provided additional insights.

Summary

Ground source heat pumps (GSHP) have a relatively small market share in multi-family houses in part due to the limited land space available for drilling. The rapidly growing market for solar photovoltaics (PV) provides an opportunity for GSHP by acting as a secondary heat source and regenerating the ground via a heat exchanger fixed to the rear of the panel. The hybrid PV/thermal collectors, called PVT, have higher efficiencies than PV only, but also come with a significant additional cost.

The primary objective of this research is to identify the technical and economic potential of PVT integration into multi-family house GSHP systems with borehole energy storage. This is achieved through a comprehensive technology review, dynamic complete systems modeling, construction of a detailed test site, and a qualitative assessment of commercial opportunities.

The results show that PVT collectors can adequately support a significant undersizing of boreholes, but that it is economical only in specific conditions. One is where the heat pump shuts down due to the excessive low source temperatures and runs on the backup auxiliary heater. The savings from drilling and the increase in seasonal performance factor (SPF) is enough to justify the additional cost of the PVT. In cases where a heat pump has been running for several years and the ground temperatures are low, PVT can lift and stabilize temperatures at a lower cost than additional drilling (assuming it is possible to do additional drilling). In cases where land area is not a limitation, the highest efficiency and lowest cost option is to drill a traditionally sized borehole field and install a PV-only system.

Integrating PVT into the GSHP is relatively simple as compared to traditional solar thermal systems. There are no changes to the hot water tank or space heating, only a heat exchanger inserted into the borehole circuit, making integration and retrofitting simple. Enabling a greater number of multi-family houses to install GSHP can reduce energy costs, primary energy demand, and carbon dioxide emissions. The form factor of modern PVT modules is the same as PV and currently qualify for government support, providing opportunities for manufactures and installers to expand their product offerings.

PVT has shown potential to help unlock the Swedish multi-family house market for GSHP and work on detailed configurations, empirical performance, and cost reductions should be the focus of future research.

Sammanfattning

Bergvärme har en relativt liten marknadsandel i flerfamiljshus, delvis på grund av det begränsade markutrymmet tillgängligt för borrning. Den snabbt växande marknaden för solceller (PV) ger en ny möjlighet för bergvärme genom att kunna fungera som sekundär värmekälla och regenerera marken via en värmeväxlare monterad på baksidan av PV-panelen. Hybrid PV / termiska kollektorer, kallad PVT, har högre effektivitet än PV, men har också ett betydligt högre pris.

Det primära målet för detta forskningsprojekt har varit att identifiera den tekniska och ekonomiska potentialen för PVT-integration i flerfamiljshus med bergvärme-system. Detta uppnås genom en detaljerad teknisk analys, dynamisk modellering av hela systemet, noggrann utformning av testinstallationen och en kvalitativ bedömning av kommersiella möjligheter.

Resultaten visar att PVT-kollektorerna kan kompensera för en betydande underdimensionering av borrhålslagret, men att denna lösning endast är ekonomisk under specifika förhållanden. Ett fall är där värmepumpen periodvis stängs av på grund av låga köldbärartemperaturer och systemet istället körs på direktelvärme. Besparingarna från borrningen och ökningen av årsvärmefaktorn (SPF) är i dessa fall tillräckliga för att motivera extrakostnaden för PVT. I de fall där en värmepump har körts i flera år och marktemperaturerna är låga kan PVT lyfta och stabilisera temperaturerna till en lägre kostnad än ytterligare borrning (om detta över huvud taget är möjligt). I de fall där tillgång till mark inte är en begränsning är det högsta effektivitets- och lägsta kostnadsalternativet att göra ett borrhålslager av traditionellt storlek och bara installera ett vanligt PV system.

Att integrera PVT med bergvärme är relativt enkelt jämfört med traditionella solvärmesystem. Det behövs inga förändringar i varmvattentank eller uppvärmningssystem, endast en PVT-värmeväxlare införd i borrhålskretsen, vilket gör integration och eftermontering enklare. Att möjliggöra för ett större antal flerfamiljshus att installera bergvärme kan minska energikostnaderna, primärenergianvändningen och koldioxidutsläppen. Måtten för moderna PVT-moduler är samma som för PV och PVT kvalificerar för närvarande för statligt stöd, vilket ger möjligheter för tillverkare och installatörer att expandera sina produktutbud.

PVT har visat sig kunna hjälpa till att öppna upp den svenska flerfamiljshusmarknaden för bergvärme och fortsatt forskning bör fokuseras på detaljerade lösningar för utformningen, empirisk bestämning av prestanda och reduktion av kostnaderna.

Contents

1 Introduction

Sweden has long been a leader in heat pumps and has one of the highest installation rates (per capita) in the world (EHPA, 2016). There are currently 1.4 million heat pumps installed in Sweden, the vast majority in single-family houses (SFH), where 90% of new homes are built with a heat pump. This market is reaching saturation, leading to a growing interest from manufacturers to grow into the multi-family housing market.

The majority of multi-family houses (MFH) are built in densely populated areas, oftentimes limiting their heating options. 85% of MFH are connected to district heating systems (Statsitics Sweden, 2013). Access to more efficient ground source heat pumps (GSHP) is limited due to the lack of land area around the building for drilling. Without adequate drilling area, the ground becomes colder which reduces the efficiency of the system, or seasonal performance factor (SPF), and thus increases operating costs. Even in correctly dimensioned systems that have been operating for 20+ years, the ground will have a reduction in temperature and if/when the owner seeks a replacement heat pump, it is likely to be a more efficient model. A higher heat pump efficiency means more heat is to be extracted from the ground and thus the borehole(s) are now under-dimensioned. Whether due to under-sizing or renovation, owners need to supplement the ground with an additional heat source, which could be solar energy.

Solar photovoltaics (PV) are the fastest growing renewable energy technology in the world (REN21, 2018). Recent growth in Sweden is due in large part to the dramatic cost reductions found in large-scale manufacturing in China and generous government subsidies (Lindahl, 2017). PV is a relatively easy renewable technology to incorporate into buildings and is the most likely candidate for increasing the renewable fractions of buildings and meeting upcoming net-zero energy building mandates. However, the efficiency of PV remains low, with rated efficiencies usually around 15-17% and operational efficiencies between 10-12%. The combination of PV with thermal energy collection in a single module, known as a PV/thermal hybrid or PVT, could increase collector efficiency from 15% to 60% or greater (Michael et al., 2015).

One limitation to this technology is the lack of a clear integration strategy, particularly with heat pumps. There are a limited number solar heat pump products on the market using thermal collectors (Ruschenburg et al., 2013), however PVT collectors require a different systems integration and control strategy due the co-generation of heat and power and the unique design of the heat exchanger. Another limitation is the lack of energy demand in the summer (Widén, 2011). With PV this leads to large sales of electricity to the grid, which can disrupt power markets. Negative pricing occurs in markets with high renewable penetration like Germany, California, Texas, and Denmark, and an impact has already been demonstrated with the increase in wind power in Sweden (Hirth, 2016). With thermal energy, there is very rarely an opportunity to sell excess heat, leading to large, extra hot water tanks for storage and/or wasted generation. The combination of solar and GSHPs can help this problem by offering a large thermal store in the borehole field.

The desire by governments and building owners for increased renewable energy and reduced carbon dioxide emissions in buildings presents an opportunity for heat pumps and solar. However, the isolated installation of these technologies represents a missed opportunity for increased renewable fractions, efficiency, and installation rates. This study seeks to quantify this opportunity and identify the potential for PVT+GSHP systems in Swedish multi-family houses.

1.1 Objectives

The overall objective of this project is to identify the technical and economic potential of solar PVT integration into GSHP systems in multi-family houses considering co-generation of heat and power and the seasonal storage of energy. This opportunity can be viewed from multiple perspectives leading to the following questions:

- What is the improvement of adding PVT to a standard GSHP system?
- Can the borehole length be reduced if PVT supplements the ground source?
- Can PVT replace supplemental drilling in undersized borehole fields?
- How much, if any, is the renewable fraction of buildings increased?

En route to answering the primary questions, several aspects of system and component design and performance will also be investigated. One important aspect that must be establish early in the study is the ideal physical integration strategy, considered from both a technical perspective and a business perspective. The use of dynamic, systems level simulation will make it possible to observe ground and collector temperatures over decades, thereby identifying the ground temperatures PVT is capable of indefinitely supporting. Due to the highly complex and integrated nature of the heat and power systems, another sub-objective is to identify key performance indicators (KPI) that fairly and accurately describe the performance of the system such that it can be compared with other technologies and systems solutions. Finally, the application of PVT plus GSHP technology is studied in existing facilities to understand how the technology can be applied practically.

1.2 Methodology

There are a variety of approaches used in this project depending on the phase of study, the objective sought, and practically available time. In the early stages a comprehensive literature review of PVT collectors and solar heat pump systems is performed, from which a qualitative analysis is performed to identify a systems design strategy with a high probability of success from a technical, economic, and business standpoint. A qualitative analysis is used in this phase due to the limited time available to perform exhaustive complex system modeling on multiple designs.

The majority of the objectives are met using a dynamic systems model built in the software TRNSYS, an acronym for TRaNsient SYStems (Klein et al., 2009). TRNSYS is a popular tool used by researchers in solar and building energy systems due to its extensive library of validated components and transparent source code. Component models are connected much like a real system (via pipes, wires, etc.) and simulated numerically until a solution is found at each time step. A detailed model description is given in Chapter 4.

The economic analysis is performed using life cycle costing (LCC), which considers realized costs over the lifetime of the system discounted back to the present day. This approach is considered state-of-the-art and commonplace in renewable energy and building efficiency analysis (Sommerfeldt and Madani, 2017). System options are compared using total life cycle cost (TLCC) where the ideal choice is the option with the least cost. When directly comparing PVT to drilling costs, initial investment will also be considered since consumer choices are often heavily influenced by initial investment (Häckel et al., 2017; Palm, 2018). All prices and interest rates used are in real terms.

1.3 Scope and Limitations

The target buildings of this project is multi-family houses in the Swedish climate and geology. The boundary conditions are represented using weather and geology conditions from the Stockholm region, which are representative of much of Sweden and Norway. The results in this model should not be directly extended to other climates and geological conditions. Sweden is currently experiencing a building boom, however the target building in this study is meant to represent a slightly older, less-efficient construction more representative of the existing building stock. Since most of the buildings in 2040 are already built today and new buildings are expected to have a much smaller energy footprint, it is valuable to focus on retrofit performance.

Due to the novel nature of this design, it was not possible to acquire measured data that could sufficiently validate the entire systems model, and therefore the results presented here should be considered as theoretical. Several pilot systems were visited, however they were either single-family houses or commercial buildings with significantly different load profiles. A large multi-family house in Stockholm provided several years of measured data on their system, which has four On/Off heat pumps used in a cascade method and no solar energy. This data, along with other theoretical models, is used as a reference to verify the long-term behavior of this TRNSYS model.

2 Technology Review

Solar heat pumps are a complex system of several technologies that as individual technologies can be considered complex systems in their own right. This chapter provides a brief state-of-the-art review for solar heat pumps, with a focus on PVT. Much more detail can be found in two papers published during the project (Poppi et al., 2018; Sommerfeldt and Madani, 2016) noted in the publication list at the end of this report.

2.1 Solar Heat Pumps

The combination of heat pumps and solar collectors has been studied for decades (Andrews, 1981; Freeman et al., 1979; Threlkeld, 1953) with the idea that the two technologies can complement each other and improve the system as a whole. The recently concluded International Energy Agency (IEA) project on solar heat pumps (Solar Heating and Cooling Task 44 / Heat Pump Program Annex 38) is the largest collection of SHP research and resulted in a useful handbook for engineers and researchers (Hadorn, 2015). Research has been predominantly focused around solar thermal collectors for single-family houses.

Just as there are numerous types of heat pumps, there are even more numerous types of solar heat pumps (SHP). Heat sources can be from the air, ground, water, or even just the solar collectors, while the sinks can be a combination of domestic hot water (DHW) tanks, combi-tanks, floor heating, traditional radiators, and so on. There are two major system configuration categories for SHP, parallel and series, and are demonstrated in Figure 1. In a parallel system, the solar energy is supplied as an alternative to the heat pump. In series, the solar energy is supplied as a supplement to the existing heat source. A third configuration, regenerative, has also been defined; however, it can be considered a subset of a series since purely regenerative configurations do not exist. With regeneration, the solar energy is used to both supplement the existing heat source and regenerate it, usually a borehole field.

Successful examples of most configurations can be found, however the most promising solutions tended towards glazed solar collectors working in parallel with the heat pump, where the baseline SPF can be increased by 1-2 (up to 35%) (Haller et al., 2014). This correlates with the types of products typically available on the market, which are dominated by glazed solar thermal collectors working in parallel with air or ground source heat pumps (Hadorn, 2015). In contrast, Buker and Riffat (2016) made a review of SHP systems for low temperature heating (i.e. buildings) and concluded that an optimal configuration could not be identified due to the wide range of possible system designs and methods for measuring performance.

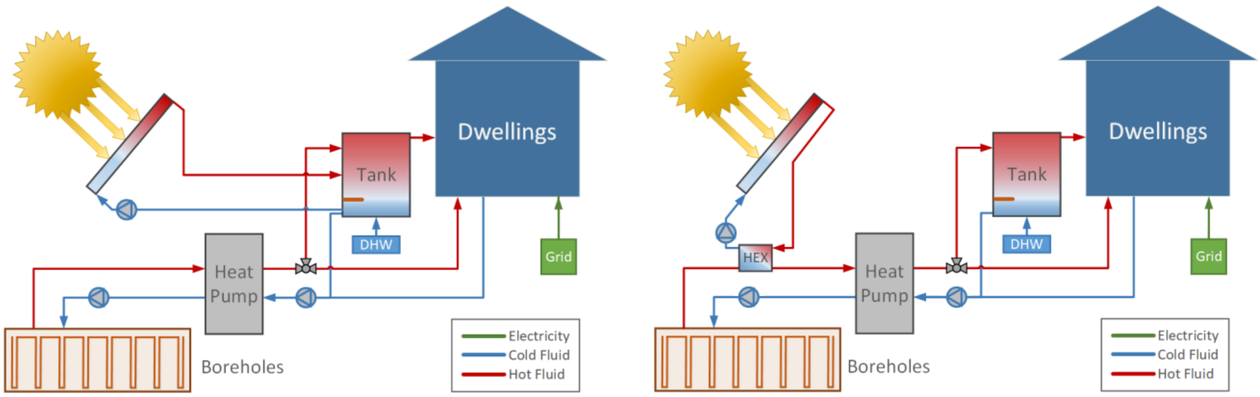

Figure 1 – Solar heat pump configurations, parallel (left) and series (right)

2.2 PV/Thermal Collectors

PVT collectors can be found in an extremely varied range of configurations and designs (Michael et al., 2015; Riffat and Cuce, 2011; Tyagi et al., 2012; Zondag, 2008). In building applications, flat plate collectors using a liquid working fluid are the most common, leaving the primary categorization in design to be between glazed and unglazed (Kamel et al., 2015), each of which are shown in Figure 2. The terminology can be misleading since an unglazed PVT collector still has a glass top surface, it is just in direct contact with the PV cells as in a typical PV module, whereas glazed collectors have an air gap to act as an insulator. A glazed collector typically has greater thermal efficiency but lower electrical efficiency than unglazed, so the design choice is partially influenced by which energy form is more important to the system. The unglazed diagram below is also uninsulated, which results in greater losses when the collector temperature is higher than ambient, but higher gains when the fluid temperatures are lower.

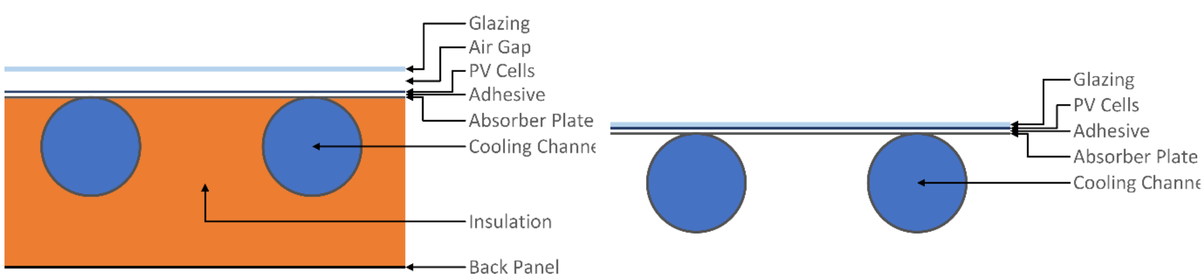

Figure 2 – Cross sections of glazed (left) and unglazed (right) PVT collectors

The operating condition of the collector in conjunction with GSHP is an important factor since temperatures can fall outside the typical operating conditions (Michel Y. Haller et al., 2012). In a series/regenerative configuration, collector temperatures can be below ambient thus making glazing or insulation a barrier to added heat gains from the ambient air. Bunea et al. (2012) tested four collector designs (flat plate, evacuated tube, unglazed-insulated, unglazed-uninsulated) with low inlet temperatures. The results show that unglazed collectors have higher efficiency during periods of low temperature or irradiance. They also showed that condensation gains could be a significant portion of the energy gains during periods of low or no incident radiation. This can be particularly helpful during winter months when heating demands are highest, but on an annual basis condensation is not likely to be a significant heat source (Bertram et al., 2010). From a product reliability standpoint, condensation inside the collector could cause damage to the materials or assembly and thus needs to be considered in the PVT design.

2.3 PVT+GSHP Systems

Although not as common as solar thermal systems, there have been several PVT+GSHP studies performed in recent years. In Germany, a new SFH was constructed with 39 m^2 of unglazed PVT collectors, a 12 kW GSHP, and 225 m (3 x 75 m each) of borehole heat exchangers (BHE) with measurements taken and compared to TRNSYS simulations (Bertram et al., 2011). Figure 3 shows the collectors connected in series and regenerating the boreholes. Measurements were taken for only two years, but they showed that the thermal demands of the house were greater than the system was sized for (mostly in DHW use). In the 20 year simulations, the PVT collectors showed a 13% greater SPF over a system without due to the higher ground temperatures. Had the system been sized correctly, the SPF would only be 6% greater.

Another SFH in Montreal, Canada was simulated by Brischoux and Bernier (2016), shown in Figure 4, which consisted of a 140 m borehole with independent dual u-tube circuits where one tube was connected to 10 m2 of unglazed PVT collectors and the other to a 10 kW heat pump. After 10 years, SPF_4 only increased from 2.82 to 2.88, a 2% improvement. The small increase is attributed to the unglazed collectors providing little benefit during the heating season, the single borehole being unable to act like a thermal store, and that the BHE was appropriately sized. A notable feature of this study was the use of multiple boundary levels for calculating SPF, and when PV generation is removed from the electricity demands of the heat pump, the SPF improves by 18%.

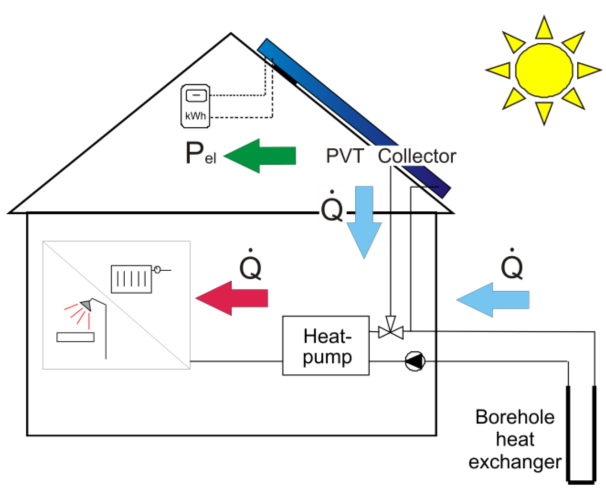

Figure 3 – A series connected PVT+GSHP system for a single-family house (Bertram et al., 2011)

In Switzerland, a low-exergy building concept presented by Meggers et al. (2012) and Baetschmann and Leibundgut (2012) includes unglazed PVT collectors combined with a novel dual-depth BHE. There are a set of 400 m deep boreholes for higher temperatures and a set of 200 m boreholes for lower temperatures. The PVT collector heat can be used directly (parallel), as a boost for the heat pump (series), or to recharge the boreholes (regeneration). The concept focuses on low temperature differences between all components in the building energy system and requires a specially designed low temperature lift heat pump. The simulations suggest that the average coefficient of performance (COP) could be near eight and a heating season SPF of six.

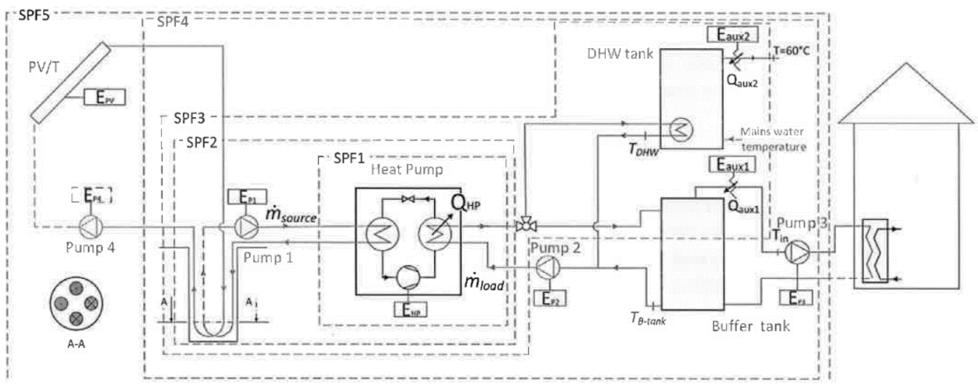

Figure 4 – PVT+GSHP using dual u-tubes in a single-family house (Brischoux and Bernier, 2016)

There are several pilot PVT+GSHP projects in Sweden, however most are not monitored for research purposes. One notable exception is a series connected system built outside of Gothenburg at BRF Vårlöken being studied by Research Institutes of Sweden (RISE) in the E2B2 program (Gervind et al., 2016). The system was built in 2013 and monitored during 2015. The borehole field is adequately sized with large spacing, meaning it will not act as a seasonal storage for solar heat, but is expected to have elevated ground temperatures over time due to the heat injection. The SPF is relatively low at 2.7 due to the need to use a backup boiler in the coldest periods and until more time passes is it not possible to see the impact the PVT has on the ground. A second simulation phase of the study is expected in 2018.

2.4 Strategies for PVT+GSHP Design

In light of the technology and literature review, the complexity of SHP systems makes objectively selecting a single best design difficult if not impossible. There are however some overarching design principles that can be combined to derive a coherent design philosophy. Unlike many previous studies, the focus here is not only technical, but also economic, meaning that cost-optimized solutions are important. This places emphasis on relatively simple components and configurations. Simplicity has been previously highlighted as a design goal for SHP systems (Dalenbäck, 1990) and complexity (or lack of expertise in management) has led to under-performance in previous systems (Heier et al., 2011).

The selected system configuration for further study is a combination series/regenerative using unglazed and uninsulated PVT collectors, shown in Figure 5. Access to the boreholes for seasonal storage is the primary element in the design. The far northern latitude of Nordic countries severely limits the potential for solar thermal energy without longer-term storage. The choice to limit the connection to the source side rather than a combination of supply/source is based on simplicity, efficiency, and cost reductions.

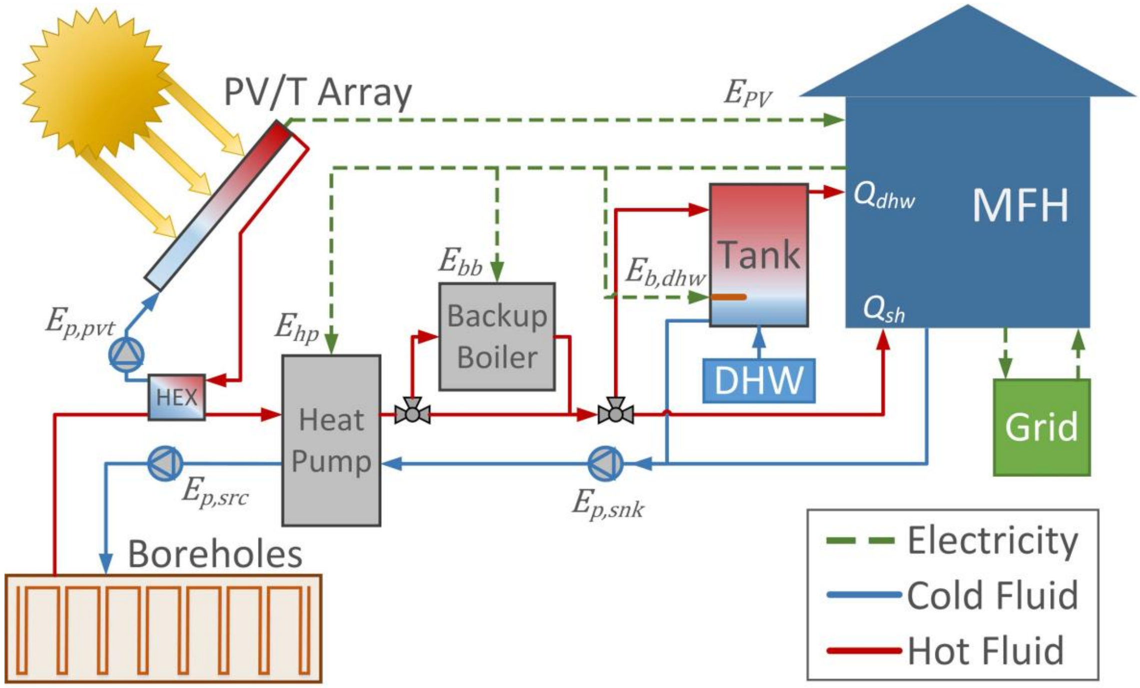

Figure 5 – Selected PVT+GSHP configuration simulated in the study

The only modification made to a standard GSHP system is the insertion of a heat exchanger into the borehole fluid circuit. This is much less invasive than a parallel configuration, which would require a different tank and likely a much larger tank (which may be space limited) to increase the collector efficiency and solar fraction. A combination parallel/series configuration, as suggested by (Kjellsson et al., 2010), is avoided for simplicity, eliminating the need for additional three-way valves and adjustments to the control system. This configuration can be easily added to an existing heat pump product or even retrofitted to existing systems. The thermal loads of most MFH are not great enough to justify a BTES, and it remains to be seen if the PVT collectors can generate enough heat for storage, however a reduction in borehole length may be a stronger economic benefit to offset the PVT investment.

The series configuration is also a better fit with unglazed collectors, which are the most common PVT design on the market and are made to look like a traditional PV module. Unglazed collectors have the advantage of much higher efficiencies when used at the low temperatures given by the borehole circuit, a critical factor in SHP design identified by Haller and Frank (2011). They also have the potential for lower costs due to less materials and even lower cost materials (e.g. polymers) due to the lower operating and stagnation temperatures.

3 Key Performance Indicators

Quantifying the performance of a complex system is not trivial, particularly when comparing multiple design choices (Poppi et al., 2018). One challenge is that some technologies or system solutions are not easily comparable, like solar thermal with hot water storage and solar PV with battery storage. Another is that many researchers create their own KPI for a unique purpose that make it difficult to compare with other studies. Efforts have been made in international research programs to standardize KPI in specific systems (Hadorn, 2015; Nordman et al., 2012), however a universally applicable framework is lacking.

The diversity of stakeholders and system solutions means it is possible (and maybe probable) that it is not possible to identify a standard set of KPI to describe all complex building energy systems. A high-level framework is proposed here to help clarify scope and objective of a given study, followed by definitions for the KPI.

3.1 Framework

The proposed KPI framework, visualized in Figure 6, is based on the clear definition of system boundary levels (BL). At the lowest level, BL1, individual components are in focus, such as solar collectors, heat pumps, or tanks. The components are influenced by the system around them, but the KPI reported remains limited to BL1. Moving up one level to BL2 brings in the supporting system(s) and connects components, such as circulation pumps and controls, and here it becomes clearer how the system behaves as a complete unit rather than a collection of parts. At BL3 the building is introduced, which includes factors technically outside of the heating/cooling system but which can directly influence the design. At the highest level, BL4, the boundaries exceed the building and take on factors from the neighborhood, city, or nation in which it sits.

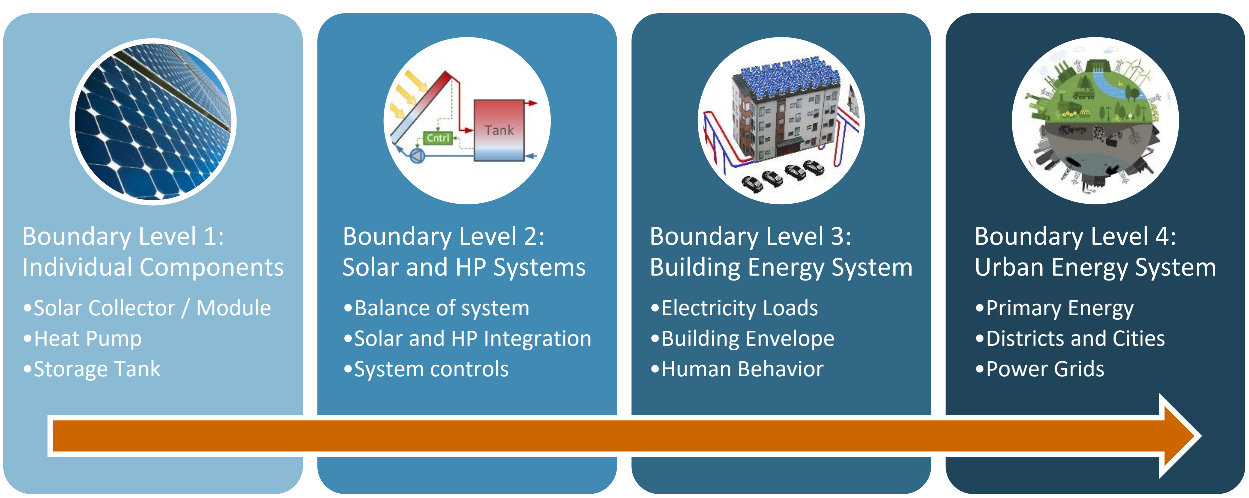

Figure 6 – Boundary level definitions for KPI Framework

The vast majority of solar heat pump studies occur at boundary levels one and two, which have been divided into narrower boundary levels by other research collaborations. Boundary levels three and four certainly have a large body of research as well, sometimes considering solar energy and/or heat pumps, but the performance of a system across all boundary levels is rarely defined. A more comprehensive discussion of this framework and relative KPI is given in the upcoming publication by the authors listed in the Project's Scientific Publications at the end of this report.

3.2 Definitions

KPI at every boundary level have been calculated during the project, however in this final report there is a limited selection from BL1, BL2, and BL4. BL1 is used to describe the specific energy generation of the PVT collectors. At BL2, the seasonal performance factor, solar fraction, and total lifecycle cost are given. BL4 is used to compare the solar heat pump to district heating, where primary energy demand is taken into account and used to calculate renewable energy fraction. CO_2 emissions from each heating technology is also given. Table 1 gives the nomenclature used in the equations.

Table 1 – Nomenclature used in KPI definitions

Symbol	Quantity
Q_{sh}	Delivered thermal energy to space heating
Q_{dhw}	Delivered thermal energy to domestic hot water
E_{hp}	Electric energy to heat pump compressor
$E_{p,src}$	Electric energy to borehole circuit (source) pump
$E_{p,snk}$	Electric energy to heat delivery (sink) pump
E_{bb}	Electric energy to backup boiler
$E_{b,dhw}$	Electric energy to backup elements in DHW tanks
$E_{p,pvt}$	Electric energy to PVT circuit pump
E_{tot}	Electric demand for entire HVAC system
$E_{pv,sc}$	PV generation used by the HVAC (self-consumed)
$E_{pv,op}$	PV generation sold to the grid
I_{HP}	Heat pump investment cost
I_{BH}	Borehole investment cost
I_{PVT}	PVT investment cost
$P_{el,r}$	Retail electricity price
$P_{el,s}$	Wholesale (selling) electricity price
RV_{PV}	Residual value of PVT system
RV_{BH}	Residual value of the boreholes
d	Real discount rate
P_{DH}	Price (per MWh) for district heating
C_{PP}	Fixed cost for district heatings peak power capacity

The specific energy of solar thermal and PV collectors are typically done with different baselines. For solar thermal, it is the heat energy produced during a given time period (usually one year) per square meter of collector area, reported in kWh/m^2-yr. The definition of collector area is not fixed, however, and can refer to the total physical area, the glazed area, or the absorber area. In this study, it is calculated using the entire physical area of the PVT array based on the PV module's spec sheet dimensions. Since solar PV can have varying efficiencies, the production per square meter is a less useful tool for comparison. Instead, specific energy is reported in terms of the energy generated per time period (usually one year) per kilowatt of rated power, given in kWh/kW_p. To demonstrate the efficiency of the collector, the electrical generation per square meter is also given in one figure.

There are numerous boundary levels that can define the electric demand of a heat pump system, but in this study every device required by the system is considered, including the compressor, circulation pumps for the boreholes, radiators, and DHW, and backup heaters. In the case of PVT systems, the solar circulation pump is also included. The motive is that the building owner will need to pay for all of the demand of these components and thus they should be included in the performance metrics. This is consistent with the SPF_4 boundary level given in (Nordman et al., 2012) defined (with PVT) below, with *Q* representing heat and *E* representing electric energy.

$$SPF_4 = \frac{Q_{sh} + Q_{dhw}}{E_{hp} + E_{p,src} + E_{p,snk} + E_{bb} + E_{b,dhw} + E_{p,PVT}}$$

A characteristic of the system configuration studied here is that all space heat and DHW is produced by the heat pump (and backup heaters), meaning all of the input energy to the system comes from electric demand. This makes solar fraction simpler in that it can be calculated using only electric energy values. However, it is important that only the PV generation used directly by the heat pump is included, not that which is used by the building or sold to the grid. There is no fixed method for classifying the application of PV generation, meaning that PV can be equally sent to any building load. But since solar fraction is defined at BL2, the heat pump system is considered the first customer to receive PV generation with any extra sent next to the building loads and finally to the grid. With this definition, solar fraction (SF) of the heat pump system is calculated by:

$$SF = \frac{E_{pv,sc}}{E_{hp} + E_{p,src} + E_{p,snk} + E_{bb} + E_{b,dhw} + E_{p,PVT}}$$

Total life cycle cost (TLCC) is used in this study due to its ease of comparison between dramatically different options. It is quite simply the cost of equipment and electricity over the lifetime of the system discounted back to present time. One challenge with this indicator is the varying lifetimes of all of the sub-systems; heat pumps are expected to last 20 years, PVT collectors can last (conservatively) 30 years, and the boreholes can last 60 years. A 20 year lifetime is considered in this study. To adjust the costing for the other equipment, the residual value of the PVT collectors (RV_{PVT}) is calculated as the present value of PV generation and the residual value of the boreholes (RV_{BH}) costing is distributed using the Equivalent Annual Cost approach. The equations for calculating TLCC for the heat pump systems are given below.

$$TLCC_{HP} = I_{HP} + I_{BH} + I_{PVT} + \sum_{y=1}^{20} \frac{\left(E_{tot} * P_{el,r}\right) + \left(E_{pv,op} + P_{el,s}\right)}{(1+d)^y} - RV_{PVT} - RV_{BH}$$

$$RV_{PV} = \sum_{y=21}^{30} \frac{\left(E_{pv,sc} + P_{el,r}\right) + \left(E_{pv,op} + P_{el,s}\right)}{(1+d)^y}$$

$$RV_{BH} = \sum_{y=21}^{60} \frac{I_{BH}}{1-(1+d)^{60}/d} * \frac{1}{(1+d)^y}$$

The TLCC for district heating is also calculated and compared to the heat pump systems. A key assumption is that DH is already installed, thereby eliminating any investment cost and only considering the operating cost. This includes the cost for heat energy and a fixed cost for peak power, a model taken from district heating operator Stockholm Exergi and represented by the equation below.

$$TLCC_{DH} = \sum_{y=1}^{20} \frac{(Q_{sh} + Q_{dhw}) * P_{DH} + C_{PP}}{(1+d)^y}$$

To compare the performance of the solar heat pump to district heating, the most common heat source for MFH, it is necessary to use BL4 in order to convert the energy used at BL2 into primary energy. For 2016, the Swedish electric grid had a primary supply fraction of 1.75 (Swedish Energy Agency, 2018), therefore any grid electricity used by the heat pump is multiplied by this factor. Boiler and distribution losses in the Stockholm heating network are reported to have a primary factor of 1.14 (Energi Företagen Sverige, 2017). The equations for calculating primary energy for the heat pumps and district heating are given below.

$$PE_{HP} = \left(E_{tot} - E_{pv,sc}\right) * 1.75 + E_{pv,sc}$$

$$PE_{DH} = (Q_{sh} + Q_{dhw}) * 1.14$$

The renewable energy fraction is also calculated at BL4, which considers primary energy. The Swedish electric grid has a relatively high renewable fraction at 34% (Swedish Energy Agency, 2018) and calculating the primary renewable energy fraction (PREF) of the solar heat pumps is done with the following equation.

$$PREF_{HP} = (1 - SF) * 34\% + SF$$

Electricity from the PVT modules is assumed free of carbon dioxide emissions, which ignores the embedded energy and emissions in their manufacture. Therefore CO_2 emissions are calculated on grid electricity only, which in Sweden is reported to be 25 g/kWh (Moro and Lonza, 2017). District heating in Stockholm is reported to have 71 g/kWh (Energi Företagen Sverige, 2017), and thus the equations for calculating CO_2 emissions are given below.

$$CO2_{HP} = \left(E_{tot} - E_{pv,sc}\right) * 25$$

$$CO2_{DH} = PE_{DH} * 71$$

4 Model Description

The core of the PVT+GSHP systems model is made in TRNSYS, which is not itself a model but more of a platform, an amalgamation of hundreds of individual models that can be connected and interact with each other. The systems model is transient but discrete, meaning that a steady state solution is found at every time step. The shorter the time step, the closer the systems model is to being fully dynamic. Naturally, this also comes with a computational cost, so there is a need for balance. This model is run using three-minute time steps, which is considered small enough to capture the short-term characteristics of the heat pump, solar collectors and boreholes with reasonable simulation times (one year takes approximately 10 minutes on a consumer laptop).

This chapter is organized by sub-systems with critical and/or supporting models described in more detail. Non-critical models (i.e. pumps, valves, or pipes) are omitted for brevity. A screenshot of the simplified TRNSYS model is given in Figure 7, which has many of the control and output components hidden for clarity. The bright green components are macros, or bundles of components that can be combined to act like a single model. Where necessary the macros will be shown in the corresponding section.

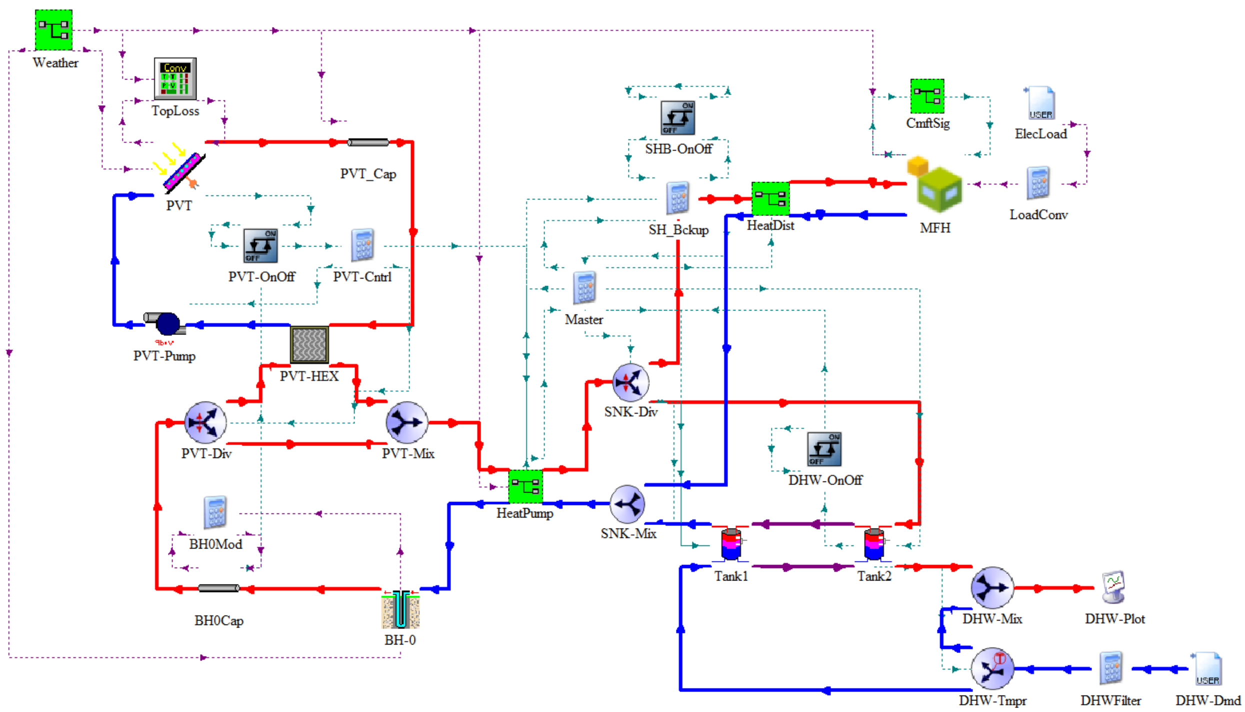

Figure 7 – Screenshot of the TRNSYS systems model

4.1 Climate

Sweden is a large and varied country for climate; however, the vast majority of the population lives in the southern 1/3 of the country. In this area, the climate is reasonably similar for a theoretical study like this and thus only a single climate is studied, which is chosen as Stockholm.

Most building simulation studies are performed using one-hour time steps, which is the typical climate file resolution. One motivation for shorter time steps is the self-consumption of PV generation by the heat pump and the building, which has been shown to be significantly different at the hourly vs. minute scale (Cao and Sirén, 2014; Salom et al., 2014). The climate file is generated using Meteonorm software (Remund and Kunz, 2018) which combines data from multiple nearby weather stations and satellite sources. The solar radiation data is generated using a stochastic model that takes hourly averages and synthesizes one-minute values (Hofmann et al., 2014). The difference in the temporal resolution is demonstrated in Figure 9, where the minute resolution shows strong fluctuations due to a partially cloudy afternoon on May 1st that the hourly data misses. The one-minute values are averaged over the three-minute time step in TRNSYS. All other weather inputs use hourly averages and the monthly averages for solar radiation and air temperature are given in Figure 8. The raw data is read into TRNSYS and solar radiation is processed using Type 16a.

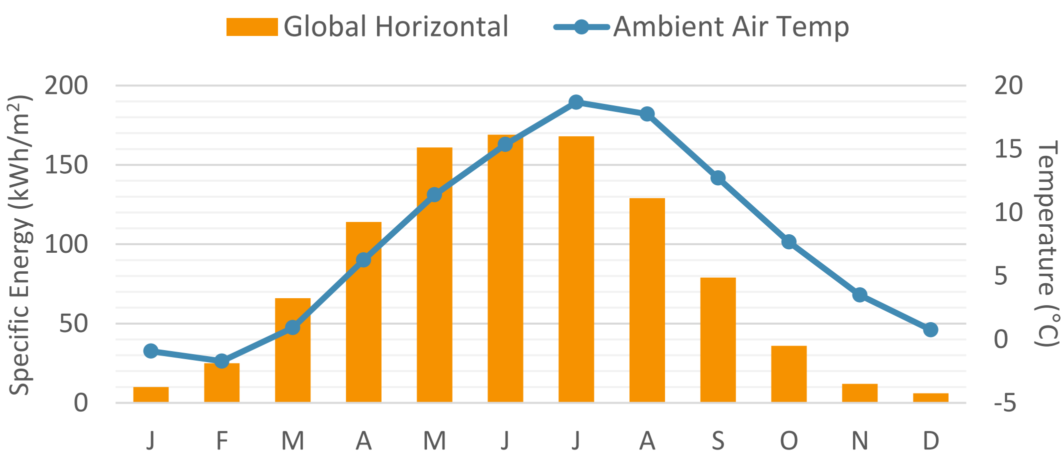

Figure 8 – Monthly average global horizontal solar radiation and air temperatures

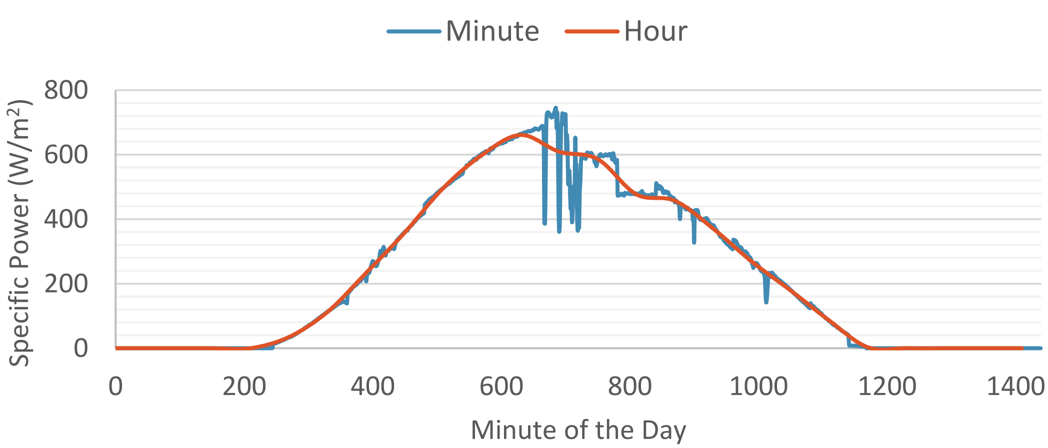

Figure 9 – Comparison of minute and hour time resolution for global solar radiation

4.2 Multi-Family House

The MFH modeled in this study is intended to represent a typical, existing Swedish MFH. The Tabula database contains several generations of building characteristics (Spets, 2012), and the construction of a 1976-1985 house with district heating is used here in TRNSYS Type 56, the multi-zone building. The shape is based on the common "Lamellhus" design, an example of which is given in Figure 10. Note that the model is not validated with loads from this exact building, only the geometry is used in combination with the construction properties from TABULA. The building is long and narrow where the long side faces south with large windows (40% window-to-wall ratio) and an unshaded roof tilted at 20°. The overall footprint of the building is 50 x 10 m with a total heated area of 2000 m^2 and a net space heating demand of 100 kWh/m^2-yr.

Figure 10 – An example of the building style modeled in the project

The heating is supplied using wall-mounted radiators and there is no heat recovery in the ventilation. The model includes eight zones divided into north/south on four floors and there is no air mixing between zones. Each zone has its own radiator and thermostatic valves that control flow rate, shown in simplified form in Figure 11. The supply temperature is set for the entire building by the heating curve at the heat pump.

The domestic hot water and internal gains are generated using a stochastic load model (Widén et al., 2009; Widén and Wäckelgård, 2010). The loads are generated in one-minute increments and then averaged to three-minutes to match the simulation time step. Internal gains are assumed as a combination of human heat and appliance use, and are applied to the zone as 80% radiative and 20% convective. Latent energy is not modeled. DHW use and internal gains are 38 kWh/m^2-yr and 56 kWh/m^2-yr, respectively. Occupant comfort is not modeled explicitly, but overheating is handled by closing the curtains when zone temperature reaches 23 °C and opening the window (effectively increasing the ventilation rate) at 25 °C.

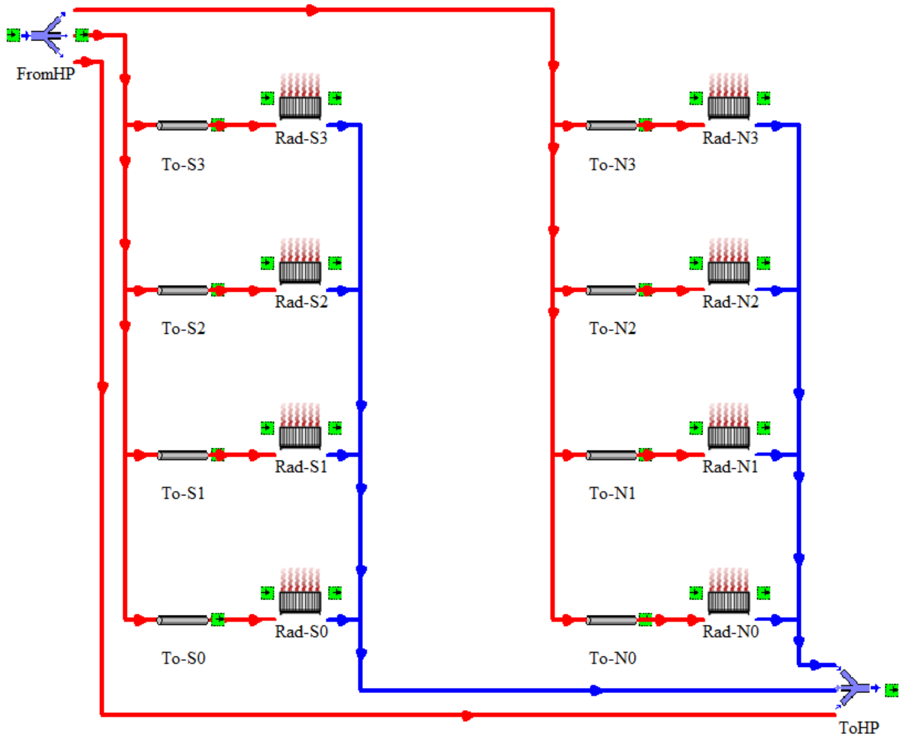

Figure 11 – Radiator distribution inside the "HeatDist" macro in Figure 7

There are two DHW tanks, 1000L each, connected in series, and modeled using TRNSYS Type 60. The tanks are fully mixed (i.e. mostly one temperature throughout) hold potable water while the heating supply is delivered through an internal heat exchanger.

4.3 Heat Pump

The model is based on a variable speed heat pump with a nominal heating power of 52 kW and seasonal coefficient of performance of 5.30 (B0/W35) at 3600 RPM. The compressor speed range is 1500 to 6000 RPM corresponding to a rated thermal power range of 21 to 88 kW. It is modeled using a multi-dimensional interpolated performance map, i.e. a black box model, a common technique in dynamic heat pump system modeling and analysis (Madani et al., 2011). The model structure is shown in Figure 12, where a three-variable interpolator accepts the source fluid temperature, supply return temperature, and compressor speed and returns the electricity demand of the compressor ($\dot{E}$) and the heat rate of the condenser ($\dot{Q}_1$). From these, the heat rate pulled from the evaporator ($\dot{Q}_2$) is calculated ($\dot{Q}_2 = \dot{Q}_1 - \dot{E}$). The flow rates vary with compressor speed to match the values used in the performance map generation, and with the heat rates on each side of the heat pump known the outlet temperatures (T_{out}) are calculated using:

$$Condenser\colon T_{out,cond} = T_{in,cond} + \frac{\dot{Q}_1}{\dot{m}_{H20} c_{p,H20}}$$

$$Evaporator\colon T_{out,evap} = T_{in,evap} - \frac{\dot{Q}_2}{\dot{m}_{BRN} c_{p,BRN}}$$

…where (T_{in}) is the inlet temperature, $\dot{m}$ is mass flow rate and c_p is heat capacity. These are applied in the *EvapHEX* and *CondHEX* components seen in Figure 12.

The compressor speed is controlled using a PI controller (proportional/integral, TRNSYS Type 23) that monitors the heating supply temperature and uses the heating curve as a target temperature. When switching to DHW preparation, the compressor speed is fixed until it returns to space heating. The space heating sends circuit sends an ON signal when 20% of the maximum flow rate is requested by the radiators and an OFF signal if the flow rate falls below 15%. This is a modeling simplification as is not intended to represent a real control system. The DHW tank sends an ON signal when the temperature falls below 50 °C and OFF when it reaches 55 °C. When the DHW and space heating both have an ON state, the priority is given to DHW. After switching between ON and OFF states, the heat pump must remain in that state for 15 minutes.

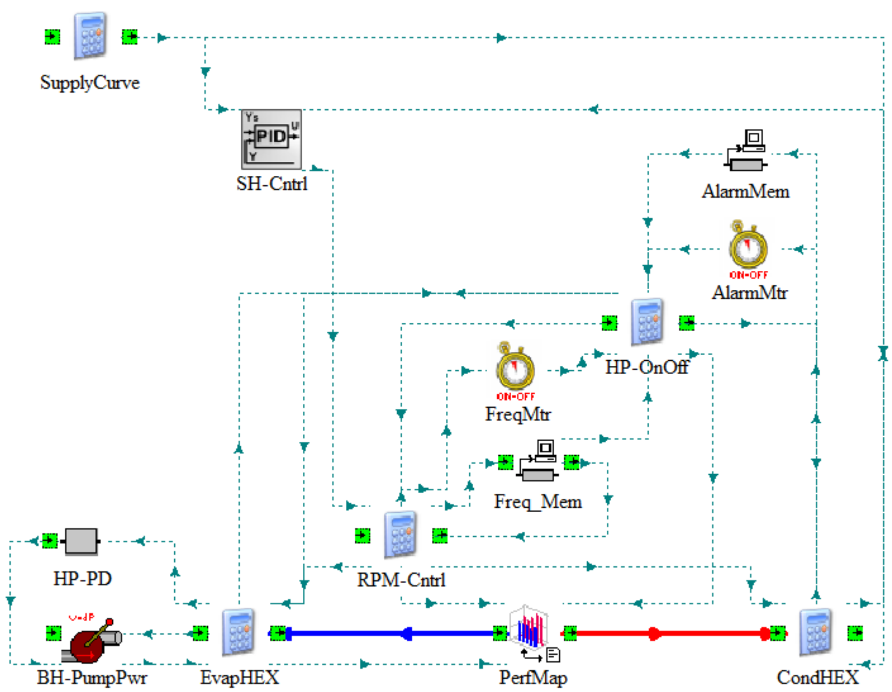

Figure 12 –Heat pump model inside the “HeatPump” macro in Figure 7

The space heating circuit and DHW tank are equipped with separate direct electric backup heaters. The DHW tank elements are switched ON if there is an ON signal from the DHW and space heating and the compressor is at its maximum speed. The space heating backup is switched ON when the compressor is at maximum frequency and the supply temperature is 2 °C below the heating curve. To protect the heat pump, the inlet temperatures to the evaporator are monitored for extreme values. If the temperatures fall below -10 °C or exceed 25 °C, the heat pump is shut down and heating is supplied exclusively by the direct electric boiler for six hours. After this time if the temperature are still out of the acceptable range, the shutdown continues and is checked again after another six hours. The temperature limits are assumed based on the secondary fluid properties, however it is important to note that installers have the ability to set their own limits and can use a higher minimum temperature than -10 °C.

4.4 Borehole Field

Borehole heat exchanger modeling is a broad and active research topic (Yang et al., 2010), and there are several models that have been adapted for use in TRNSYS (Michel Y. Haller et al., 2012). The most commonly used is Type 557 based on the Duct Storage model (DST) originally developed by Hellström (1989) and validated by Pahud (1993) due to its inclusion in the TESS library of components available from the makers of TRNSYS. It is difficult to use alternatives due to the lack of widespread distribution, oftentimes requiring personal contact with the original authors or personally programming the algorithms.

The DST model was developed specifically for modeling BTES systems. It assumes a compact array of equally spaced boreholes within a cylindrical volume and solves two problems, local and global. The local problem is the volume surrounding the borehole field and is solved using a 1-D numerical method. The global problem denotes the region between the field volume and the far field, and is solved using a 2-D finite difference scheme. Because of its intended application, Type 557 is sometimes considered inappropriate for non BTES applications or non-uniform field geometry (Casetta, 2012; Kummert and Bernier, 2008) and instead analytical solutions using a g-function are promoted (Hadorn, 2015). However, Type 557 has been shown to perform acceptably well against measured data (Spitler et al., 2009). Its accessibility, flexibility, and ability to model borehole fields (many models can only simulate a single borehole) motivates its use in this study.

Another criticism of Type 557 is its poor short term response behavior due to solving the heat transfer problem for steady state conditions (De Rosa et al., 2014; Kummert and Bernier, 2008; V. Godefroy, C. Lecomte, M. Bernier, 2016). A work-around solution has been validated by Pärisch et al. (2015) by adding a plug-flow pipe model connected to the boreholes. This gives the secondary fluid thermal capacity, and to simulate heat transfer during shut down periods they circulated the fluid continuously to model convective heat transfer.

A pipe model is added in this study equal to the borehole length x2 plus 100 m for the distance to/from the building, however the method for modeling heat transfer during residence is simplified. The pipe has a fixed heat transfer rate, which is then lost (i.e. not connected to boreholes or ground). During periods with flow, the temperature outside the pipe is set equal to the inside, effectively eliminating any heat transfer outside of Type 557. During periods of no flow, the temperature outside the pipe is set to the borehole wall temperature, which effects the internal energy of the resting fluid. Since the heat pump being modeled is variable speed there is flow in the boreholes for 80% of the year and On/Off cycles are limited. When PVT is included, the boreholes are always being circulated, limiting the short-term modeling errors in the boreholes.

The thermal characteristics of the ground model are set to represent typical Swedish granite with ground water filled boreholes (Acuña, 2013). There are several borehole field geometries tested, which are described in the results section. Table 2 gives the main thermal and geometric parameters of the baseline case. This field is sized according to the ASHRAE method implemented in GeoDesigner (Rolando et al., 2015) using the modeled space and DHW loads from TRNSYS. The model is Type 557a, which uses borehole geometry and thermal properties to calculate borehole thermal resistance. The fill conductivity is higher than that of water due to small convective effects, and is used to tune the resistance to 0.1 K-m/W (Acuña, 2013). Ground water flow is not considered both for simplicity and because it is not possible with Type 557. The working fluid used in the borehole circuit is a 30/70 ethanol-water mixture.

Table 2 – Thermal and geometric properties of the baseline borehole field

Parameter	Value	Units
BH Depth	275	m
BH Number	12	-
BH Spacing	20	m
BH Diameter	0.15	m
Header Depth	5	m
Ground Conductivity	2.8	W/m-K
Ground Thermal Capacity	2016	kJ/m^3-K
U-tube Inner Diameter	0.036	m
U-Tube Outer Diameter	0.040	m
Shank Spacing	0.080	m
BH Fill Conductivity	1	W/m-K
Pipe Conductivity	1.5	W/m-K

4.5 PVT Collectors

There are two main branches of analytical PVT collector models, theoretical and quasi-dynamic (Pressiani, 2016). Theoretical models use the collector geometry to determine the heat transfer characteristics, and most use traditional fin-and-tube designs originally derived by Hottel and Whillier (1955) for solar thermal collectors and modified for use with PVT (Florschuetz, 1979). Quasi-dynamic models use a polynomial to describe thermal efficiency considering (at a minimum) irradiance, mean fluid temperature, and ambient air temperature. A more advance model has been developed which also considers wind speed (M.Y. Haller et al., 2012) and condensation (Stegmann et al., 2011). The benefit of quasi-dynamic models is that they are relatively simple and use performance coefficients from standard testing procedures (EN12975). However, when simulating a collector that is still in the prototype phase and has not been tested, a theoretical model is more useful.

One of the project partners, Solhybrid i Småland, is working to bring PVT+GSHP systems to market, and has been developing their own PVT collector. The geometry of their most recent prototype is used and applied in TRNSYS using Type 560, a theoretical model included in the TESS library. The prototype is utilizes a custom Perlight 280W monocrystalline glass-glass module and a metal heat exchanger mechanically pressed to the rear surface. The collector is categorized as unglazed and uninsulated. The geometry of the prototype is known, however a critical assumption in the thermal resistance between the PV module and the heat exchanger is not. Data from dynamic testing performed at RISE was used to determine the thermal resistance and convective heat transfer coefficients (external and internal) (Sommerfeldt and Ollas, 2017).

The remainder of the PVT circuit consists of a pipe for adding fluid capacity, similar to the borehole model, a single-speed pump, and a plate heat exchanger to connect to the borehole circuit. The pipe is sized to include the volume of fluid in the collectors (this is not captured in Type 560) and the piping to and from the mechanical room. The pump model considers pressure drop and flow rate in calculating power requirements, however pressure drop is fixed at 50 kPa due to complexity of capturing the necessary adjustments to the plumbing that would be made when changing the array size and/or flow rate. The heat exchanger has a constant effectiveness of 80%, which usually results in a 1 K temperature drop between fluids. The working fluid in the PVT circuit is a 40/60 propylene glycol-water mixture.

Control of the PVT pump is made with a simple temperature difference between the outlet temperature of the collector and the outlet temperature of the borehole field. When the temperature at the PVT is high enough above the borehole circuit, the circulation pump turns on. This difference is the cut-in temperature. To avoid rapid on/off cycling of the pump, the cut-out temperature difference is lower than the cut-in by a few degrees. The difference between the cut-in and cut-out is called the deadband. A parametric analysis is presented in section 5.2 to determine the optimal settings for the flow rate, cut-in and cut-out temperatures.

The roof of the MFH is made to be ideally suited for solar energy; south facing, 20° tilt, and unshaded. Since the building is only four floors, the roof is also quite large relative to the floor area. The south-facing roof area is 266 m^2, and once setbacks and collector geometry are taken into account, the maximum array size is 144 collectors equaling 236 m^2 and 40 kW_p of rated PV power. A parametric analysis of smaller PVT arrays is presented in the results.

4.6 Economic Models and Assumptions

Equipment costing is highly uncertain, particularly with GSHP due to the wide variety of ground conditions between sites. With the help of project partners Avanti Systems and Bengt Dahlgren, a survey of drillers was conducted to create a model for borehole drilling costs based on the number of holes drilled (BH_{cnt}) and their depth (BH_{dpth}). Drilling cost is found to be much more strongly related to depth than in total number and resulted in the following equation (in SEK/m) based on a regression analysis of the survey results.

$$I_{drill} = (1 - 6.34 \times 10^{-5} * BH_{cnt}) * \left(158.53 + 3.38 \times 10^{-4} * {BH_{dpth}}^2\right)$$

This model only represents drilling costs. For u-pipe collectors, manifolds, additional ground work, working fluids, and commissioning and additional 100 SEK/m is added, resulting in total borehole installation costs between 270 and 290 SEK/m (without VAT).

A fixed investment for the heat pump, plumbing, installation, and commissioning is added to the borehole cost such that the system corresponds with the Swedish industry norm of approximately 15,000 SEK/kW of heating capacity for GSHP.

The investment cost model for PVT collectors is broken into three components; the collectors, install cost per collector, and a fixed installation cost. PVT collectors are assumed to be 5000 SEK each based on quotes from suppliers in Europe and Solhybrid. Installation has a fixed cost of 130,000 SEK plus an additional 3000 SEK per collector. This model gives specific installation costs (SEK/m^2) at the bottom of the normal range for solar thermal systems in Denmark (Weiss and Spörk-Dür, 2018). PV system investments are calculated using a fixed 12 SEK/kW$_p$, which is consisted with larger MFH systems (Lindahl, 2017). All prices are without VAT. Both PVT and PV systems are assumed to receive the 30% investment rebate currently available in Sweden.

The retail electricity price is assumed to be 1.2 SEK/kWh and the wholesale price 0.3 SEK/kWh, similar to typical prices in 2017 (Nord Pool Spot, 2018). When selling to the grid, PV generation earns the wholesale price plus 0.15 SEK/kWh in green certificates and 0.60 SEK/kWh as a micro-producer bonus. The green certificates last for 15 years and the bonus for five years. Prices are fixed for the lifetime of the analysis and are assumed to be real (i.e. do not include inflation). The discount rate is also real, and is assumed to be 3%.

District heating prices are taken from Stockholm Exergi (2018) using the recently updated “Fjärrvärme Bas” price structure. A 100 kW peak power is assumed, leading to an 83,000 SEK per year fixed fee. The energy price is 245 SEK/MWh in the summer (April-October) and 624 SEK/MWh in the winter. Stockholm Exergi also incentivizes customers to have low return temperatures, charging an additional 20 SEK/MWh for each degree above 50 °C and giving a -6 SEK/MWh per degree below 50 °C. For the building used in this study, this correlates to an additional 2.5% in annual costs for each degree above 50 °C and a reduction of 0.7% for each degree below. Since district heating is not modeled explicitly, bonuses and penalties associated with return temperature are not included in the costing.

5 Modeling Results

The approach to this study, as described in the introduction, is to describe the impact a PVT system can have on the performance of a GSHP system. The experimental results describe an ideal control strategy for the PVT collectors, the influence of individual borehole field parameters, three reduced-length borehole scenarios, reduced PVT array sizes, and the ground response to PVT installation of an already cooled ground. A more detailed description of the PVT-GSHP system's behavior is given as an introduction before the long-term performance results. Economic and environmental results are presented for the reduced-length scenarios and a limited sensitivity analysis on economic inputs is given. The baseline GSHP system given in the Model Description is used as an anchor point to place the remaining results into perspective, and while the results baseline are given in detail among the other results, a brief summary to describe the system is given in Table 3.

Table 3 – Baseline GSHP performance summary

Parameter	Year 1	Year 10	Year 20
SPF_1	3.71	3.61	3.56
SPF_4	3.44	3.33	3.27
Electricity Demand (MWh/yr)	78.6	81.1	82.6
Avg. BH Wall Temp (°C)	5.4	3.8	2.9
Avg. Evaporator Inlet Temp (°C)	5.0	3.4	2.5

5.1 PVT+GSHP System Behavior

The results in this section provide a detailed description the PVT-GSHP behavior over a year. They are given as an example to provide greater clarity on energy flows and how the long-term results can be achieved. The system simulated is the baseline GSHP with a 144-collector PVT array. Naturally, alternative system configurations and later years of operation will give slightly different results, but the general concept remains the same.

In Figure 13, the heat flows of the evaporator and the PVT collector are given. On the left, the *Evaporator Demand* represents the thermal demand input required by the heat pump, which would normally be provided exclusively by the borehole field. *PVT Supply* is the thermal energy delivered from the PVT array. The graph on the right shows the distribution of the PVT Thermal supply between the heat pump and the boreholes, identifying the time when PVT and heat pump operations correlate. Approximately 45% of the PVT energy is fed directly into the heat pump, which elevates the secondary fluid temperature above the level it would normally be without PVT.

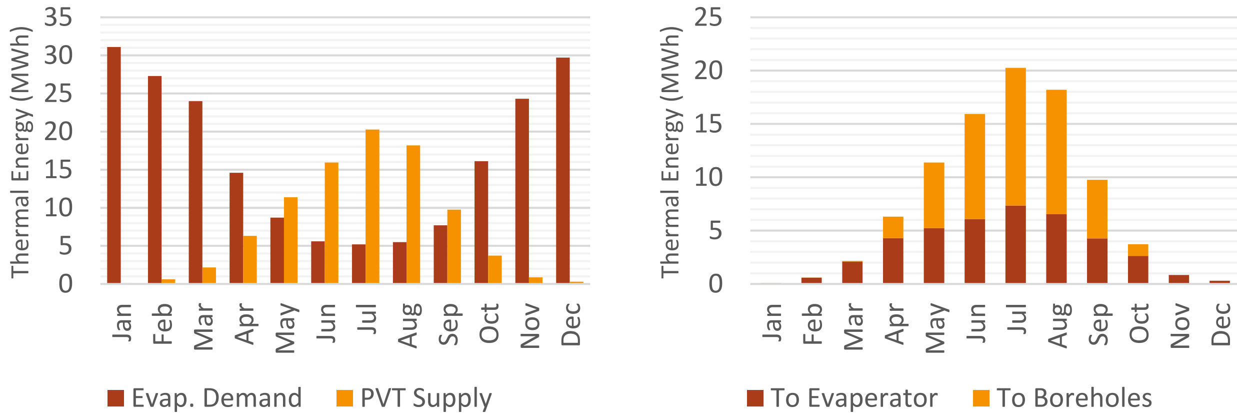

Figure 13 – Thermal energy flows in the PVT-GSHP system

The elevated temperatures in the secondary fluid are demonstrated in Figure 14, where the average hourly temperatures of the secondary fluid are given. The baseline and PVT to HP temperatures are measured at the evaporator while PVT to BH are the fluid temperatures delivered to the borehole field. As would be expected, the temperatures are much higher during the summer due to the additional PVT input, which accounts for approximately 15% of the heat to the evaporator over the year (with 144 collectors).

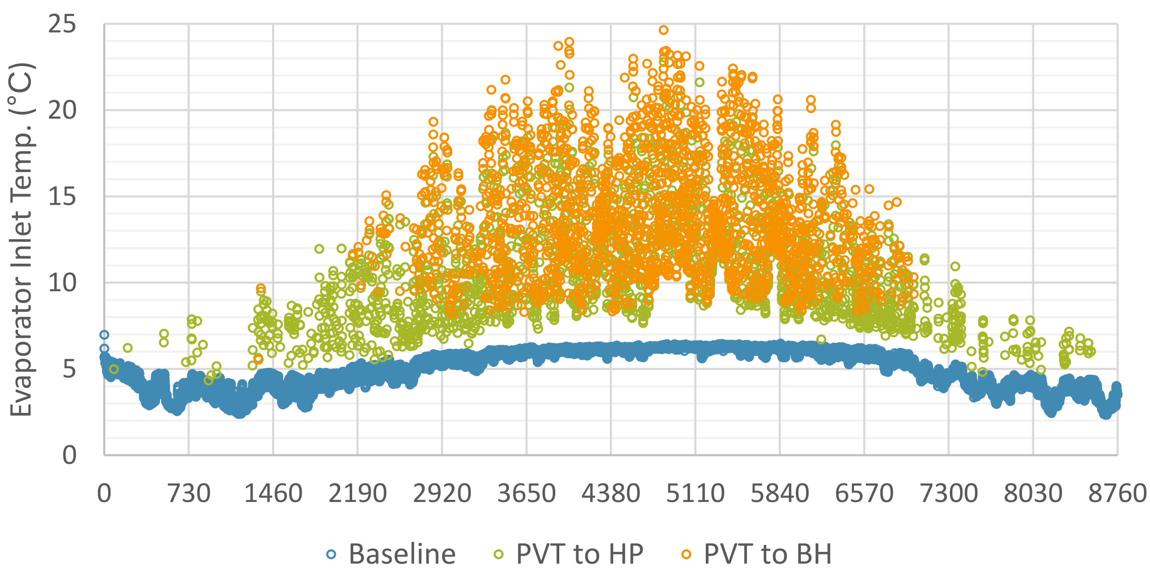

Figure 14 – Evaporator inlet temperatures with and without PVT

Shifting the viewpoint from the heat pump to the boreholes, Figure 15 shows the thermal extraction and injection rates in the PVT+GSHP system where extraction is negative. Between the months of May and September there is a net positive load on the boreholes, meaning the ground temperatures will recover faster than a non-SHP system. The ratio of extracted to injected heat is approximately 3.5 to 1, even with a full roof of PVT. This suggests that a BTES, where the ground temperatures are elevated above the undisturbed level, is not possible.

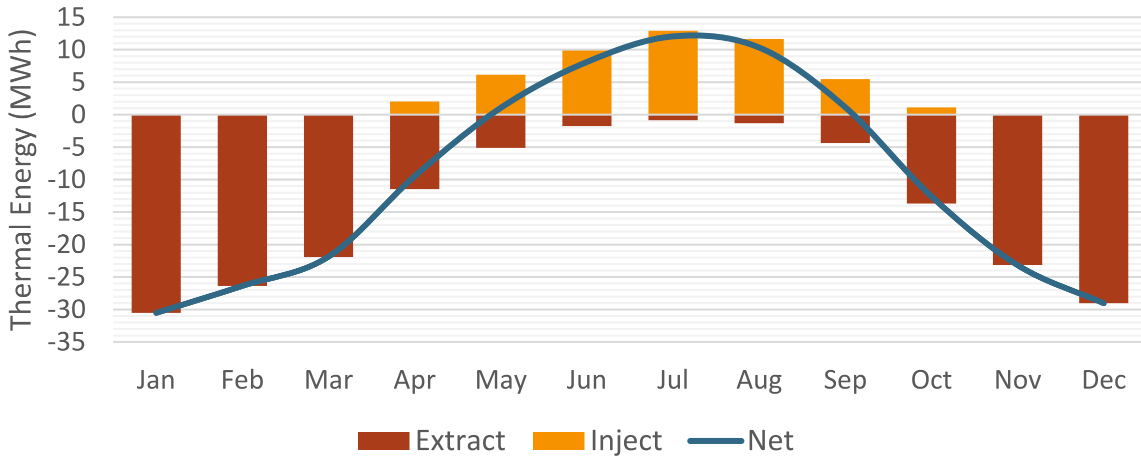

Figure 15 – Borehole thermal energy flows with PVT

Similar results for electrical energy flows are given in Figure 16. The left hand graph shows the electrical demand of the heat pump as compared to the electrical generation of the PV cells, with high levels of over-production during the summer months. On the right hand graph the flow of electricity to three locations is given; the heat pump, the remainder of the building, and the grid. These results assume that the heat pump is the primary customer of the PV electricity and that only unneeded generation is then delivered to the rest of the building. This could also be reversed, which would theoretically reduce the PV electricity used by the heat pump.

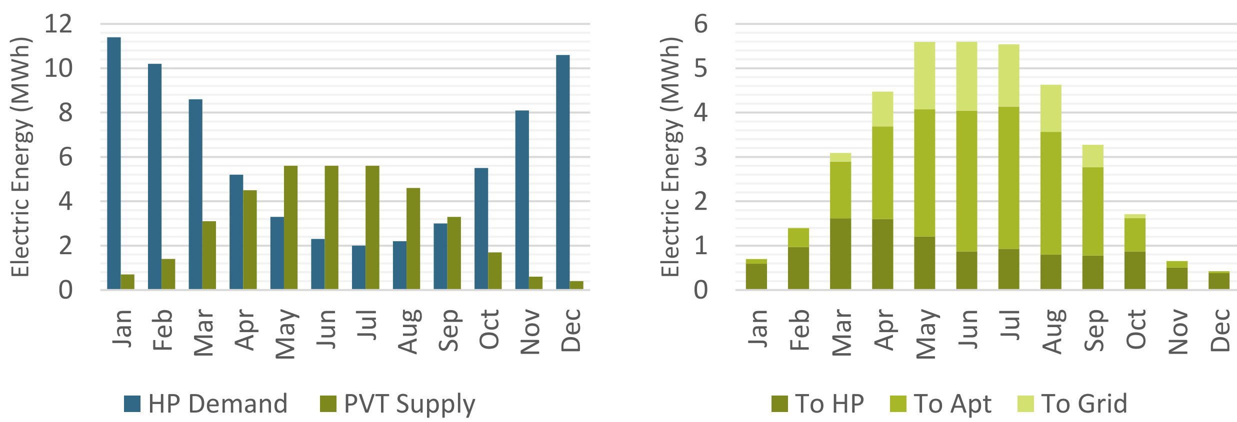

Figure 16 – Electrical energy flows in the PVT-GSHP system

5.2 PVT Pump Controls

A parametric analysis is used to identify the PVT circulation pump controls that will produce the greatest net savings of electricity for the system. The test system has 144 PVT collectors and the baseline borehole field (12 holes, 275 m deep, 20 m spacing). As mentioned in the Model Description, the pump is single-speed and controlled using a simple deadband method. This analysis parametrically tests the specific flow rate, cut-in, and cut-out temperatures according to the values given in Table 4. The cut-in and cut-out temperature combinations are limited such that only a minimum deadband of 2 K is permitted.

Table 4 – PVT circulation pump controls values for parametric analysis

Parameter	Unit	Range	Step
Specific Flow Rate	l/hr-m^2	10-90	10
Cut-in Temperature	K	3-6	1
Cut-out Temperature	K	1-4	1

The results in Figure 17 show a wide range of thermal gains for a given flow rate or pumping energy. Between 10-30 l/hr-m^2, there is a notable increase in thermal gains, which then flatten out at higher rates. While the points within each flow rate make a recognizable pattern in Figure 17, there is no consistent relationship with cut-in and cut-out temperatures within each flow rate. Logically, the larger the deadband the longer the pump runs, increasing both thermal gains and pumping energy. However, the benefit of a larger deadband is less at higher flow rates.

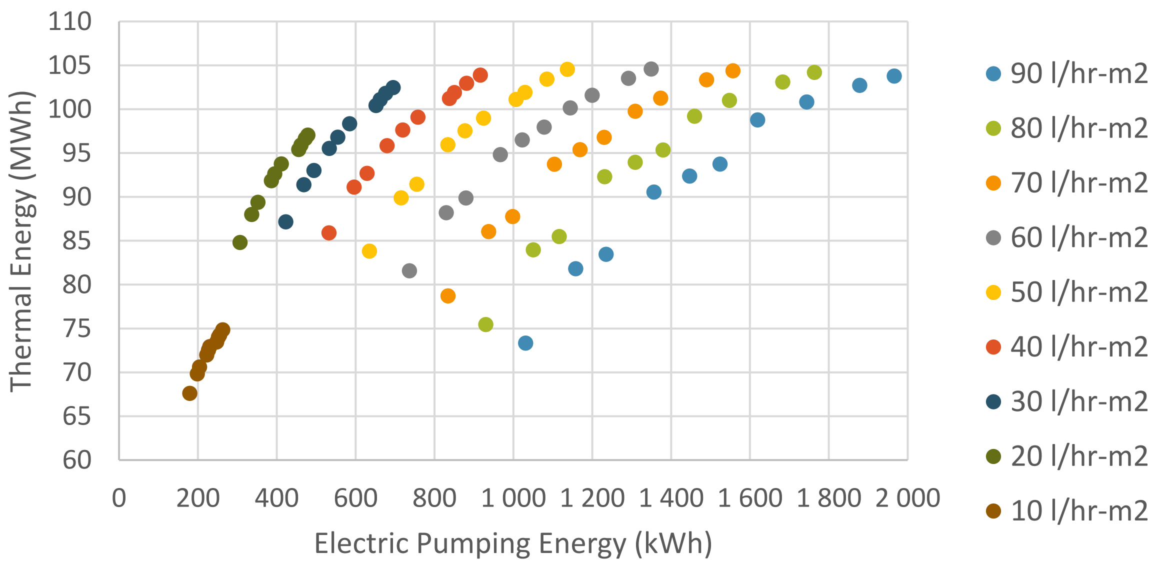

Figure 17 – PVT thermal energy extraction versus required pumping energy

The ultimate purpose of the thermal PVT energy is to reduce the overall electrical demand of the heat pump system, therefore the controller should be optimized around the net savings between the reduced heat pump demand and the additional energy required by the circulation pump. Figure 18 shows the best performing temperature controls for each flow rate, with cut-in and cut-out temperatures above each column, as well as the separated electrical savings and cost. The results show a minimum value at 20 l/hr-m^2. The temperature controls at this flow rate have little impact on the net savings, with a less than 10% difference between the minimum and maximum. However, the optimal control has a cut-in temperature at 6 K and cut-out at 1 K. This strategy is used for the remainder of the study.

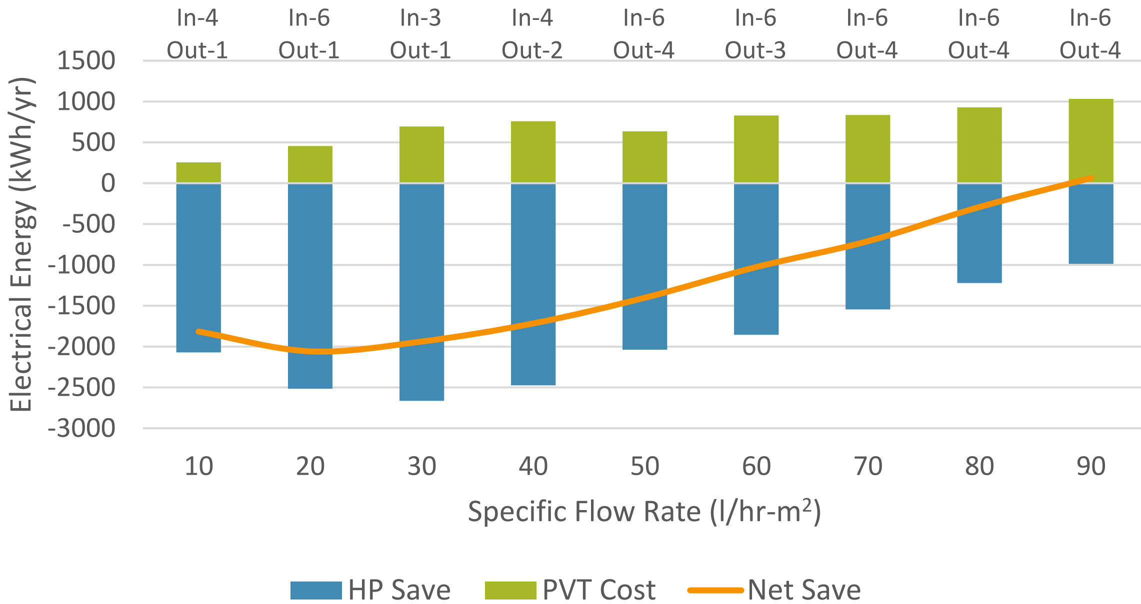

Figure 18 – Annual electric energy savings and cost of the heat pump and PVT circulation pump

5.3 Borehole Parametrics

Borehole fields have three primary geometrical dimensions: depth, count, and spacing. Combined these three values create the volume of earth used as the heat source and it is interesting to see how each individually influences the performance of the heat pump and how the PVT can assist. The range of values tested are given in Table 5, and in each case the base values of the other parameters are fixed. Only depth and count influence the total length of the boreholes, however spacing influences the interactions between them. The baseline field has 12 boreholes, 275 m deep, with 20 m spacing, for a total length of 3300 m. In all cases, a 144-collector PVT array is simulated.

Table 5 – Borehole field geometry values for parametric analysis

Parameter	Unit	Range	Step
Depth	m	275 - 110	65
Count	-	12 - 6	2
Spacing	m	20 - 5	5

The first presented parameter is depth and SPF_4 over a 20-year lifetime is given in Figure 19. As would be expected, there is a clear reduction in SPF with shorter boreholes. Over the lifetime, the 110 m deep holes would require 13% more electricity than the full 275 m depth. The addition of PVT improves the average lifetime SPF by 2.5% to 6.8% for the 275 and 110 m depths, respectively. In year 20, the SPF of the 110 m depth is improved by 10%.

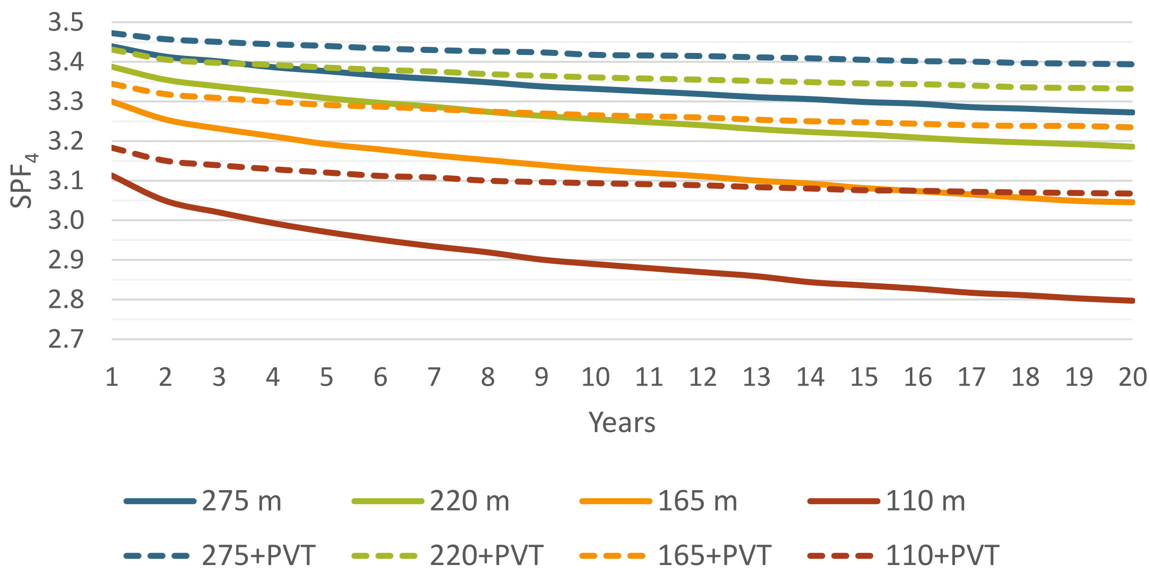

Figure 19 – SPF_4 over a 20 year lifetime as a function of varied borehole field depth

The improvements to SPF are visible in the borehole outlet temperatures, shown in Figure 20. In the first years there is little difference, but over time borehole recharging maintains higher ground temperatures. During the peak heating months in year 20, the average temperature is nearly 4 °C greater with PVT. It can also be seen that the temperatures without PVT have very low minimum temperatures, with a minimum circuit temperature (at the evaporator outlet) of -11 °C. TRNSYS does not alter fluid properties during the simulation, meaning the higher viscosities experienced with lower temperatures does not affect pumping power. It may also be the case that to avoid damage from freezing, an installer will prevent such low temperatures by running exclusively on the backup heater, a topic explored further in the discussion.

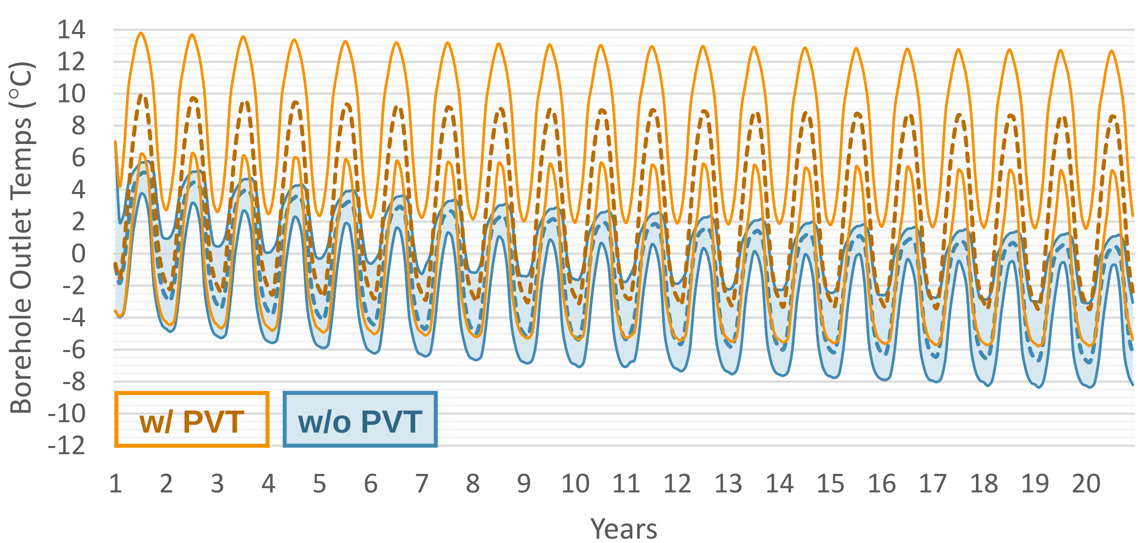

Figure 20 – Borehole field outlet temperatures for the 110 m deep borehole case

Reducing borehole count has a similar impact to the SPF, shown in Figure 21, as the reduced depth. The results are not directly comparable here since the percentage reductions of overall length are different in each case, but reducing the count by 50% increases electricity usage by 11% over the 20 year lifetime. The PVT has as similar impact as well, improving the average SPF in the six borehole case by 4.8%. This is slightly worse than the average between the 110 and 165 m cases above (which would equal 50% length reduction), but within the model's uncertainty.

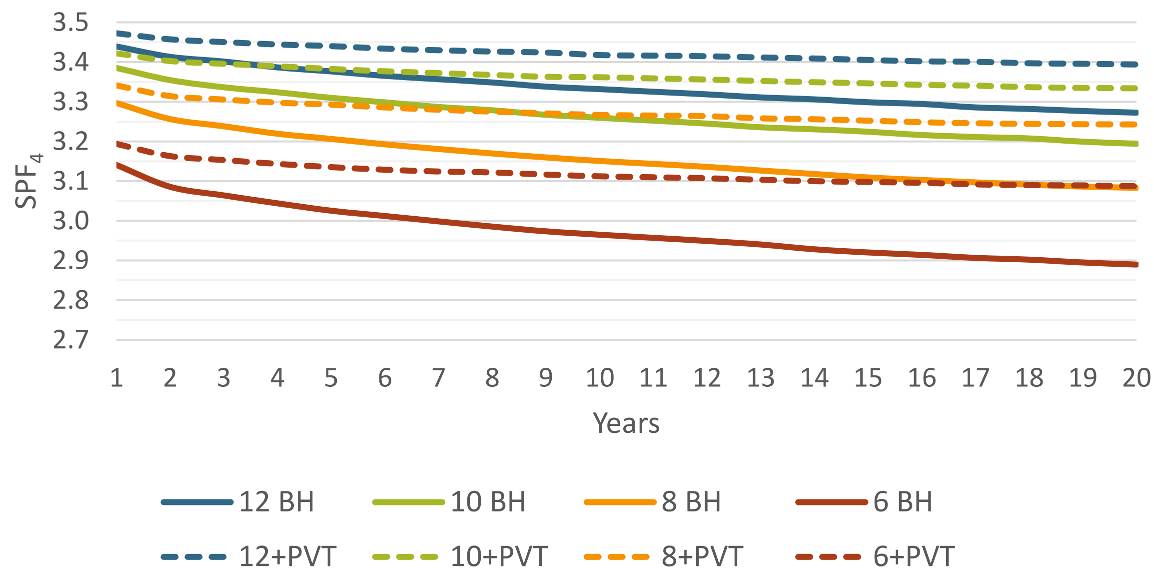

Figure 21 – SPF_4 over a 20 year lifetime as a function of reduced borehole count

The improved SPF is reflected again in the borehole fluid outlet temperatures, shown in Figure 22. The average temperature during peak heating season in year 20 is on average 2 °C higher.

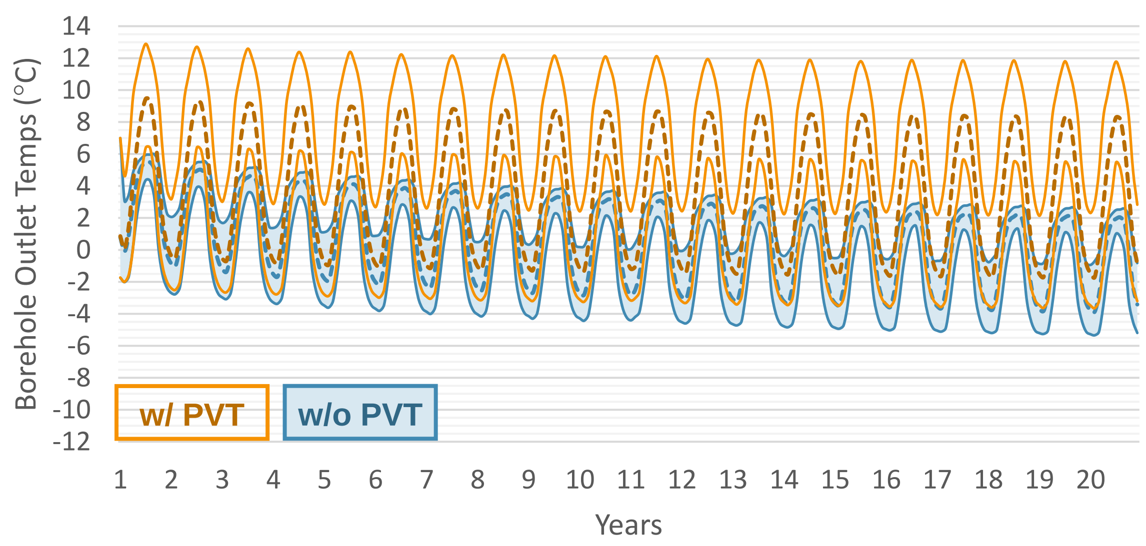

Figure 22 – Borehole field outlet temperatures for the six borehole case

Borehole spacing differs from the other two parameters in that it does not reduce the overall borehole length, maintaining a constant heat exchanger area in each case. As Figure 23 shows, in the extreme 5 m spacing case the lifetime SPF is reduced by 7.6% from the 20 m case. Interestingly, the 5 m case with PVT has nearly the same SPF as the 20 m case without. The rate of decline in year 20 is also much lower with PVT collectors, essentially stabilizing, whereas the non-PVT systems will continue to decline.

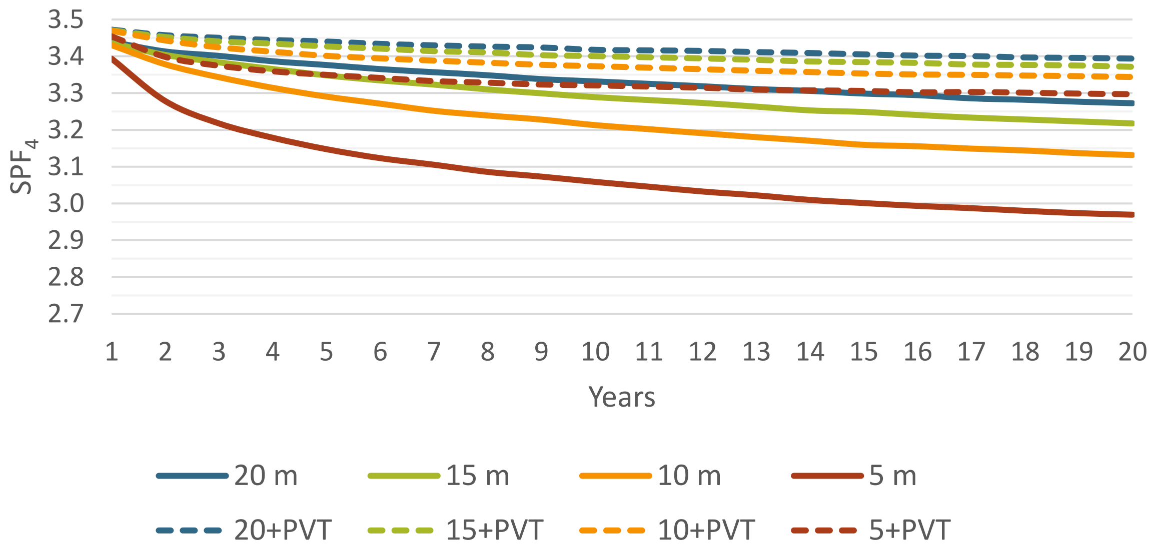

Figure 23 – SPF_4 over a 20 year lifetime as a function of reduced borehole spacing

A notable difference in the borehole fluid temperatures given in Figure 24 is the reduced amplitudes and narrower bands for minimums and maximums as compared to the reduced length borehole fields shown in Figure 20 and Figure 22. This is likely a function of having the full borehole length available for high power extraction events in winter and solar injection in the summer.

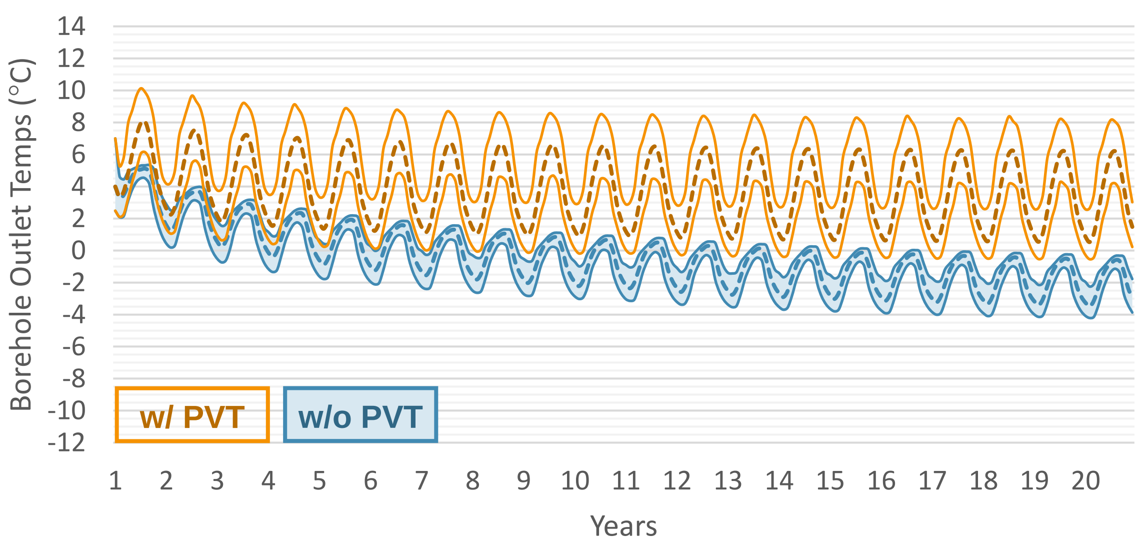

Figure 24 – Borehole field outlet temperatures for the 5 m spacing case

5.4 Borehole Combinations

The parametric study on borehole geometry helps describe the influence of individual parameters, however it may often be the case with MFH that a combination of reduced borehole length and spacing may be necessary. This section presents results of three scenarios where the borehole fields are reduced in depth, count, and spacing at the same time. There are nearly infinite number of potential combinations so this study does not claim to cover the full range of possibilities, but it does present extreme situations that could be used as a reference point for future case studies. Table 6 lists the geometry of each scenario, which are named for the percentage of total reduced length to the base case.

Table 6 – Borehole geometry for the combined reduced size scenarios

Scenario	Depth	Count	Spacing	Length
Base	275	12	20	3300
25%	250	10	15	2500
45%	225	8	10	1800
65%	200	6	5	1200

The SPF results given in Figure 25 show a more dramatic situation than the parametric results. The 25% and 45% scenarios are comparable to the reduced depth or count, however the 65% scenario is much worse, having an SPF in year 20 of 2.1. This is due to the need to shut down the heat pump during much of the heating season from year five and onward due to excessively low borehole fluid temperatures. The markers for the 65% scenario for years 17-20 are to indicate that these results are extrapolated. The controller in the simulation became unstable and caused a divergence in the solution. However, trend in SPF is easily extracted to complete the figure.

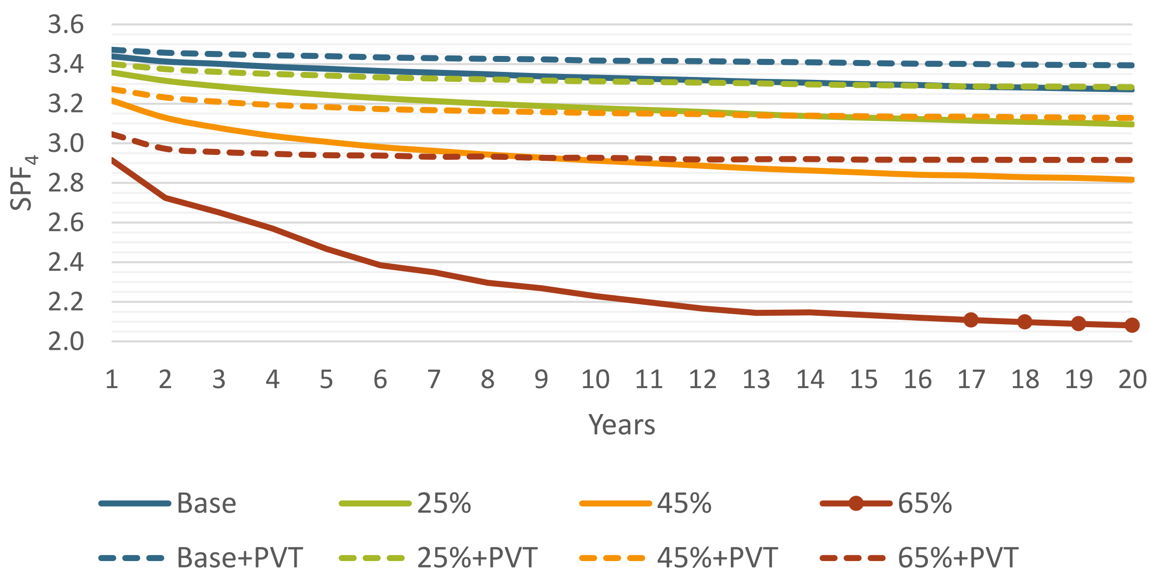

Figure 25 – SPF_4 for reduced borehole field scenarios over a 20 year lifetime

Over a 20 year lifetime, the 65% reduction requires 31% more electricity to operate than the base case. The PVT array is able to increase the average SPF by 27% and by 40% in year 20. The borehole temperatures shown in Figure 26 clearly show the limit being reached already in year five and increasing across the heating season over time. Unlike SPF, the fluid temperatures are not easily extrapolated and thus the results without PVT are omitted after year 16. The amplitude of the PVT array is very high, with minimum temperatures still reaching -8 °C, however the system shows stability in that the ground and SPF values should remain in a steady state.

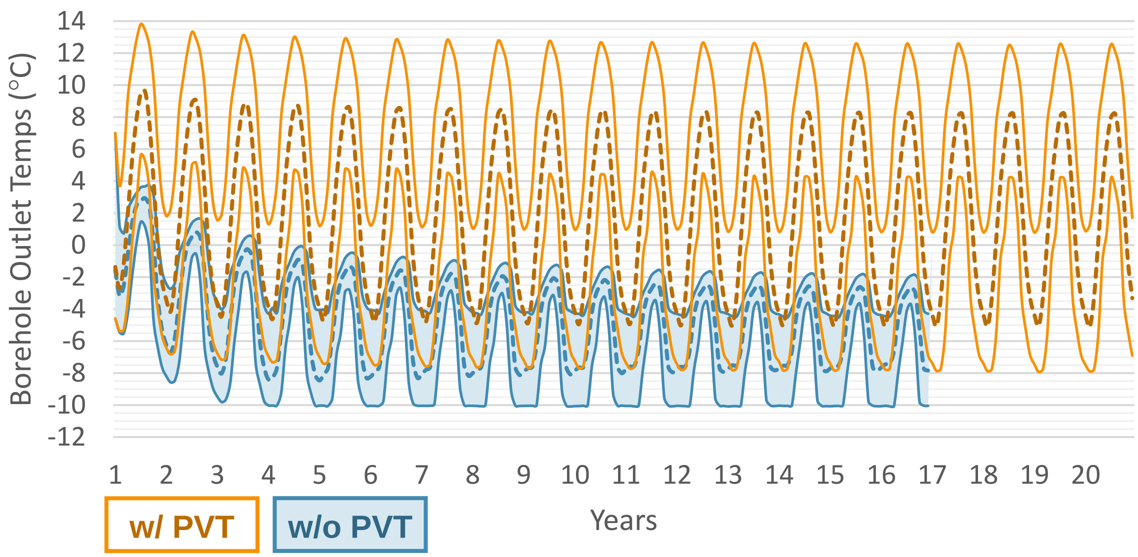

Figure 26 – Borehole field outlet temperatures for the 65% reduction scenario

5.5 PVT Parametrics

The roof space and orientation of this study's building is purposely made to represent a best-case scenario for solar energy. However, the vast majority of MFH have much smaller roofs or roof space relative to their floor area. In this parametric analysis, the 65% scenario from the previous section is used to test the impact of smaller PVT array areas. Table 7 reports the sizing of each of the smaller arrays.

Table 7 – PVT array sizing for parametric analysis

Collector Count	Area (m^2)	PV Rating (kW_p)
144	236	40.3
120	196	34.2
96	157	26.4
72	118	19.8
48	79	13.2

The results in Figure 27 show that there is a diminishing return with increasing PVT collector area. The 48 collector array is 1/3 the area of the 144 array, but only uses 28% more electricity over the 20 year lifetime. In year 20, the 48 collector array can recover 85% of the SPF reduction between a system without PVT and the 144 collector array.

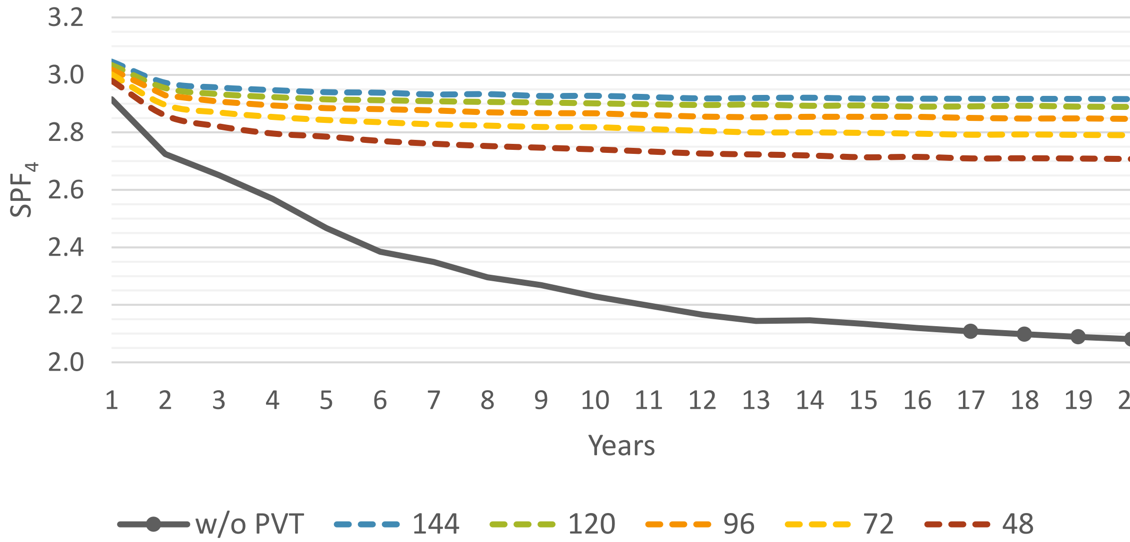

Figure 27 – SPF_4 for reduced PVT arrays in the 65% scenario over a 20 year lifetime

The dramatic improvement comes primarily from the reduction of auxiliary boiler use. Figure 28 shows that without PVT, the -10 °C minimum acceptable inlet temperatures are reached in year 4, which is when the heat pump shuts down. With 48 collectors, the borehole circuit is relatively cold, with average heating season temperatures around -8 °C and minimums of -10 °C. In this case, it is possible the auxiliary boiler will be triggered during the coldest days, particularly after year 20. It is important to note again that the heat pump can operate down to -10 °C, but the limit on many installations are set higher.

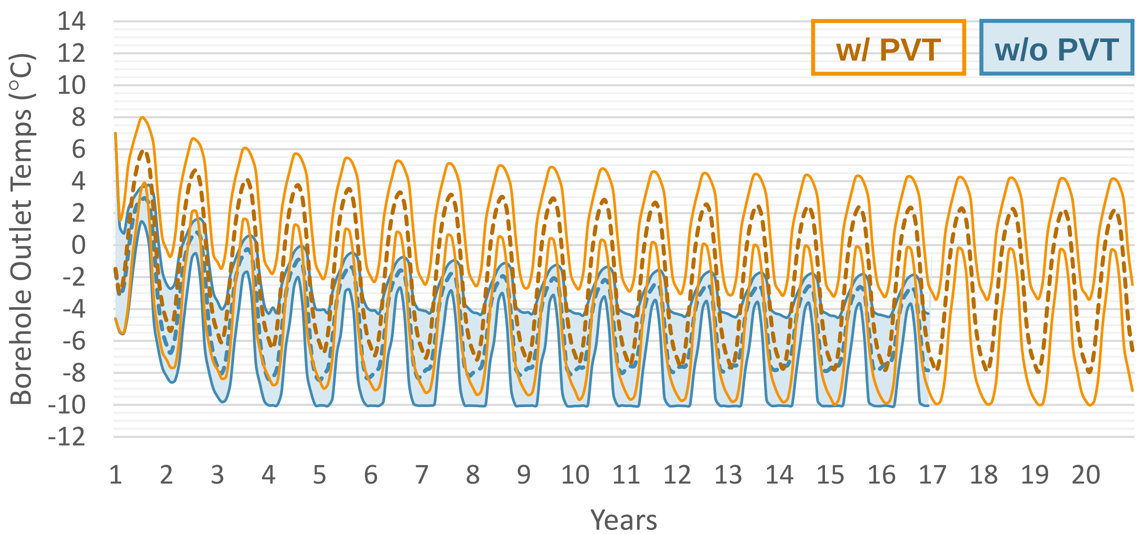

Figure 28 – Borehole temperatures for a 48 collector PVT array in the 65% scenario

5.6 Life Cycle Cost Analysis

The technical results have shown that PVT arrays improve the performance of GSHP systems, however these savings come with an addtional cost. In this section, the total life cycle cost is presented to compare the savings from reduced drilling to the cost of adding PVT collectors. Since PV-only systems are the current standard for rooftop solar, they are also included for comparison. District heating (DH) is also included since the vast majority of MFH in Sweden currently have their heating supplied by DH.

From the results in Figure 29, it can be seen that adding 144 PVT collectors to a sufficiently sized borehole field will add cost to the system that is not returned in electricity savings. PV systems however, will reduce the cost of energy for the building. This pattern holds for each of the reduction cases until the 65% scenario, where HP-only, PVT and PV systems have nearly the same cost. This is due to the significant change in SPF (and thus electricity use) from the auxiliary boiler, which the PVT array is able to reduce in the 65% case. Much less auxiliary heating is needed in the other scenarios. In all cases, the heat pump based systems have a lower life cycle cost than DH, up to 35% cheaper in the 45% case with PV. This result highlights the expense of drilling as compared to the low price of electricity in Sweden, but does not take into account the risk of damage due to low borehole temperatures.

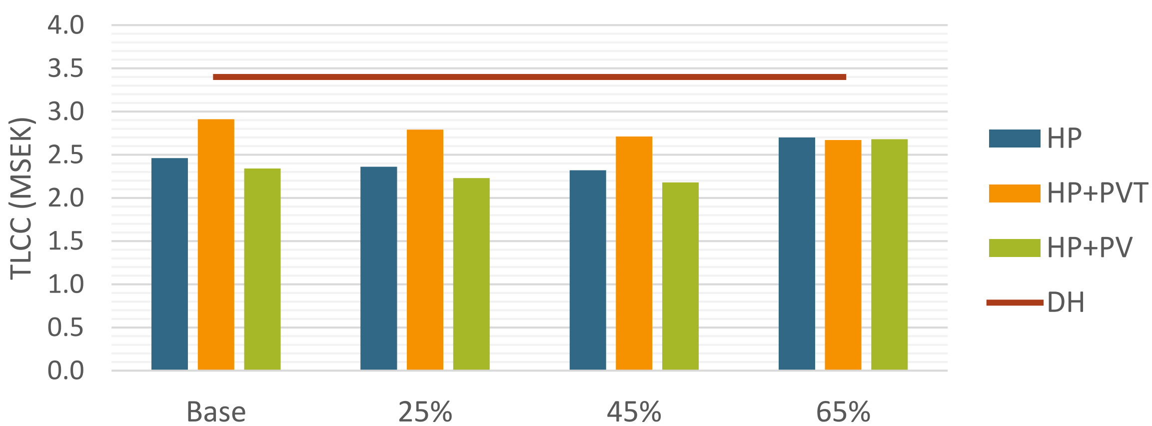

Figure 29 – Total life cycle cost of HP, SHP, and DH heating with 144 PVT or PV collectors

The PVT parametric analysis in section 5.5 demonstrated that a large collector array is unnecessary to gain much of the benefit in SPF. Figure 30 shows the life cycle cost of the baseline system to the 65% scenario with reduced PVT array sizes. The *144* results are the same as the *65%* results in Figure 29. Here it can be seen that the smaller PVT systems become the more economical due to lower investment costs. However, the savings are relatively minor, with an 8% reduction of cost in the 48 collector case from the 144 due to the higher use of electricity. If electricity prices were to rise, this savings would be less or could even cost more than installing 144 collectors. The impact of electricity pricing is discussed in section 5.9.

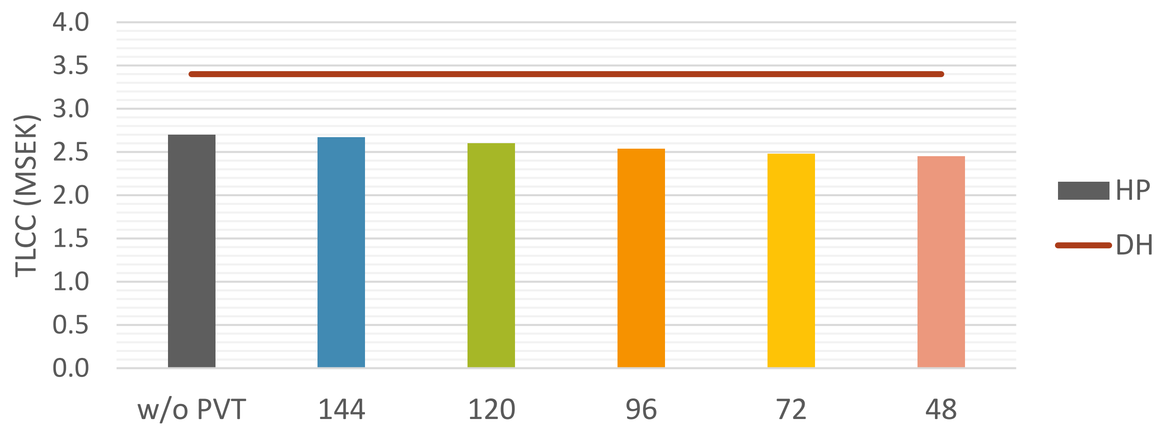

Figure 30 – Total life cycle cost of reduced area PVT+GSHP systems in 65% scenario

5.7 Adding PVT to Existing Systems

As mentioned in the introduction, one possible application for solar heat pumps is in the retrofit of existing systems. In this test, the 65% scenario is run for 10 years and then a PVT array is added in year 11, where 144, 96, and 48 collector arrays are considered. A common response to an undersized borehole fields is to drill additional holes, therefore this option is also tested by adding four, eight, and twelve holes to the six originally installed with the system. Due to limitations with Type 557, the additional holes must be the same depth (200m) and spacing (5m) as the original field.

Figure 31 shows the results of new drilling (solid lines) or adding PVT (dashed lines) in year 11 as compared to no new installation (6 BH) and installing PVT at year 1 (Y1 PVT). As expected, there is a sharp increase in efficiency when the new equipment is added due again to the reduction of auxiliary boiler use. The PVT collectors also cause a sharp response in the first year that slowly tapers off as it reaches its steady state.

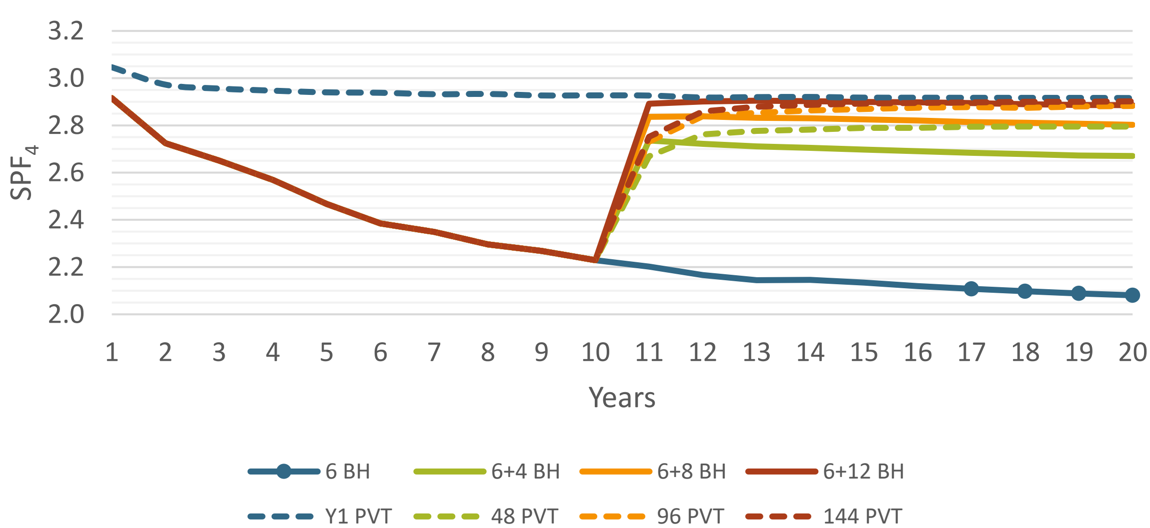

Figure 31 – SPF_4 for boreholes and PVT arrays added in year 11

Comparing the installation of 144 collectors in year 1 or year 11, the performance is nearly identical by year 20. Looking at the borehole fluid temperatures in Figure 32 for the 144 collector addition, it can be seen how quickly the temperatures are lifted away from the critical point where the auxiliary boiler is triggered. It is also important to note that after year 20, the newly drilled boreholes will continue to degrade (slowly) while the PVT+GSHP system is already at or near its steady state point. This indicates a potential for PVT to indefinitely support undersized borehole fields at any point in their lifetime, however the stabilized borehole temperature should be checked for potential freezing in water filled holes.

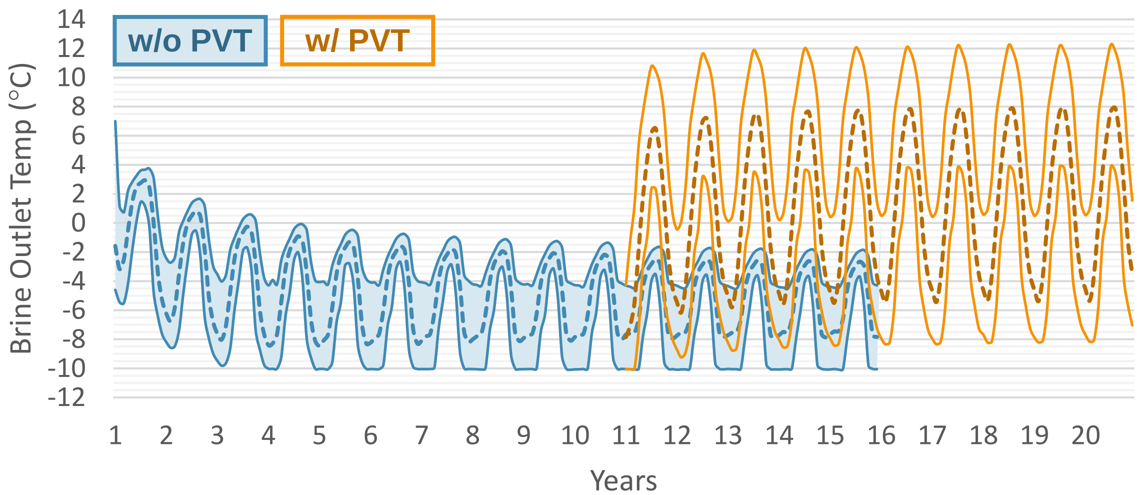

Figure 32 – Borehole temperatures with a 144 collector array installed in year 11

Similar to earlier results with installations in year one, the smaller arrays are able to deliver more improvement per square meter than the larger arrays. Comparing the PVT to drilling in Figure 31, the 48 collector array is able to deliver similar performance as the addition of eight boreholes. Assuming there is the space to drill so many new holes, this would cost approximately 670 kSEK (with VAT), while the PVT array would cost 575 kSEK (with VAT) without subsidies. Including the current 30% capital rebate the cost is reduced to 400 kSEK. Additionally, the PVT array would deliver electricity that reduces operating costs over simply adding boreholes, further improving the economics of the system.

5.8 PVT Collectors

One of the motivations of using PVT collectors in a series arrangement is that both the thermal and electrical efficiencies can be higher than in a parallel arrangement. In this section, the generation of the PVT array from three configurations is compared: the 144 collector array with the baseline borehole field, the 144 collector array in the 65% scenario, and the 48 collector array in the 65% scenario. These cases are the most extreme examples and are chosen to highlight the impact the PVT and borehole fields have on each other.

The first metric, mean PVT collector fluid temperature, is shown in Figure 33. Both 144 collector cases have similar summertime temperatures, but the much smaller borehole field in the 65% scenario results in lower wintertime temperatures. With the smaller 48 collector array, temperatures are lower year round. When the systems reach steady state after about 12 years, the 48 collector array operates 5K colder than the 144 collector array in the summer. Annual average fluid temperatures at steady state are 6.2, 4.5, and 1.2 °C for the 144-Base, 144-65%, and 48-65% cases, respectively.

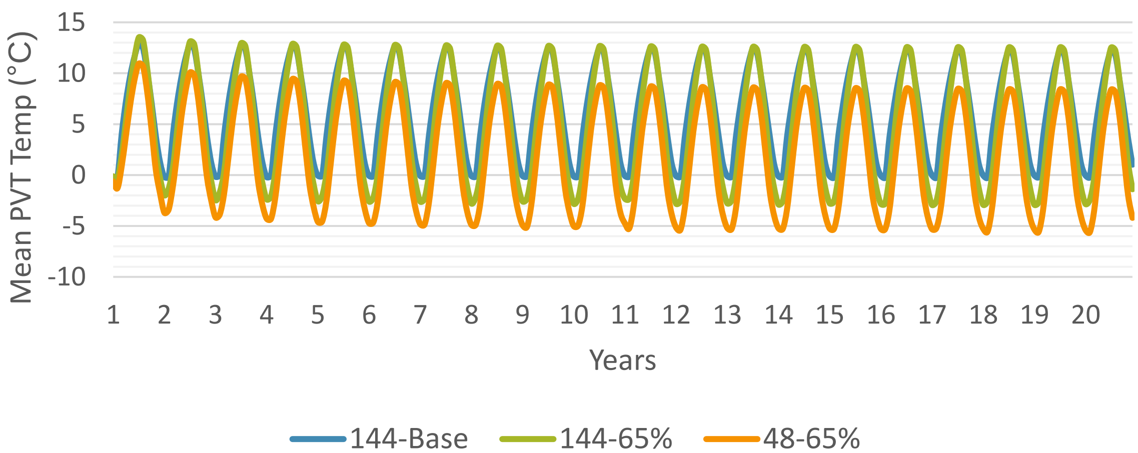

Figure 33 – Monthly mean PVT working fluid temperature in three cases

Lower inlet temperatures will result in higher efficiencies, but it will also result in more runtime. As discussed in section 5.2, the cut-in and cut-out temperatures are the same in all cases, 6 and 1 K, respectively. When the borehole temperatures are lower than the ambient air, the PVT pump will stay on longer, even during winter months. This is clearly seen in the monthly runtimes shown in Figure 34. The 144 baseline case never runs for more than a few hours in the winter since the borehole temperatures are relatively high. The 48-65% case only shuts down during the coldest periods since the average borehole circuit temperature is usually below -6 °C during winter months. In these cases the PVT array acts as an air-to-water heat exchanger, not only a solar collector. In the summer months during peak solar generation, all configurations are running non-stop. When the system reaches steady state (after about 10 years), the 144-Base, 144-65%, and 48-65% cases run for 4250, 6670, and 8250 hours per year. The extremely high runtime of the 48-65% scenario is motivation to reexamine the control strategy, as the low cut-out temperature may cause the pump to run during such cold periods that the gains are less than in the base case that was used in the parametric analysis in section 5.2.

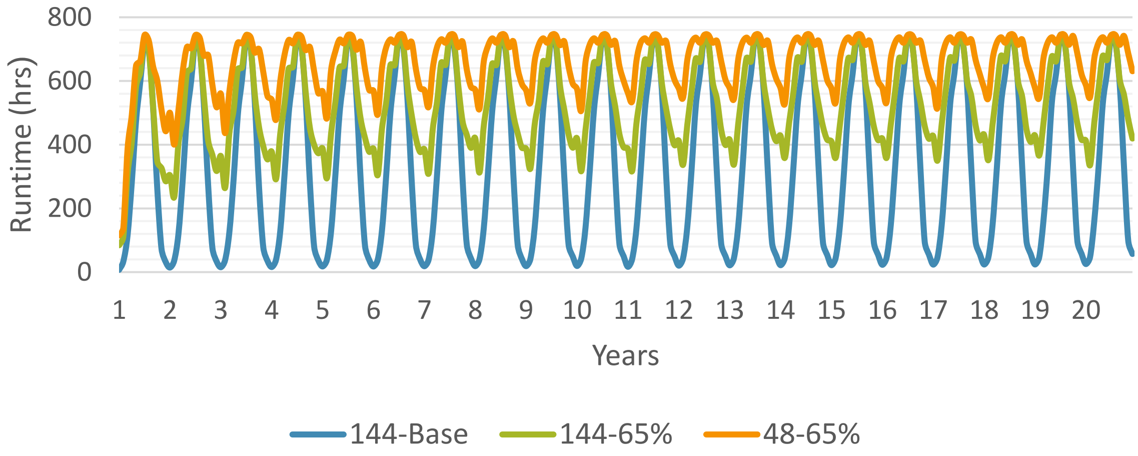

Figure 34 – Monthly PVT circulation pump run time in three cases

The lower fluid temperatures and the longer runtimes combine to give the 48 collector array much higher specific heat generation, shown in Figure 35. Specific generation is given in kWh_{th}/m^2 per month to normalize the comparison between the different sized arrays. It is clear from the figure how much more productive the 48 collector array is, which delivers 30% more thermal energy per m^2 in the summer than the 144 collector arrays once steady state is reached. The greater wintertime production can be attributed to the 48 collector array operating more often than the other cases.

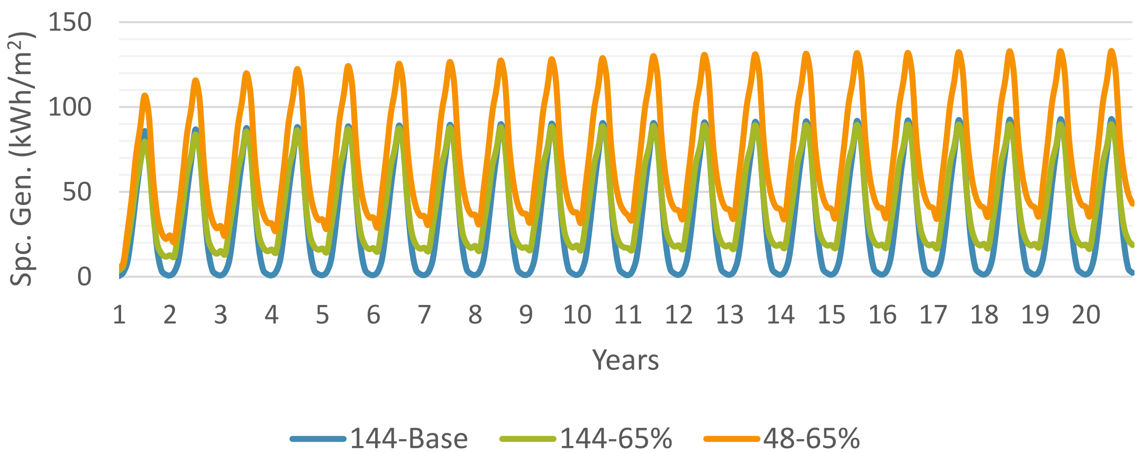

Figure 35 – Monthly specific thermal generation in the three cases

The annual specific generation is a commonly used indicator for solar collector performance. In Sweden, glazed solar thermal systems operating in parallel typically generate 300-450 kWh_{th}/m^2 per year (Mauthner and Herkel, 2016). The annual specific generation for the three cases are shown in Figure 36, with both thermal and electrical generation. The 144-Base case is within the typical range, while the 65% scenarios are more productive, much more so with the 48 collector array, which begins approaching 100% total efficiency (based on 1136 kWh/m^2–yr of solar radiation striking the PVT array).

Much of the thermal energy is actually captured from the air, so it can be misleading to say it is 100% solar efficient, but the performance is noteworthy.

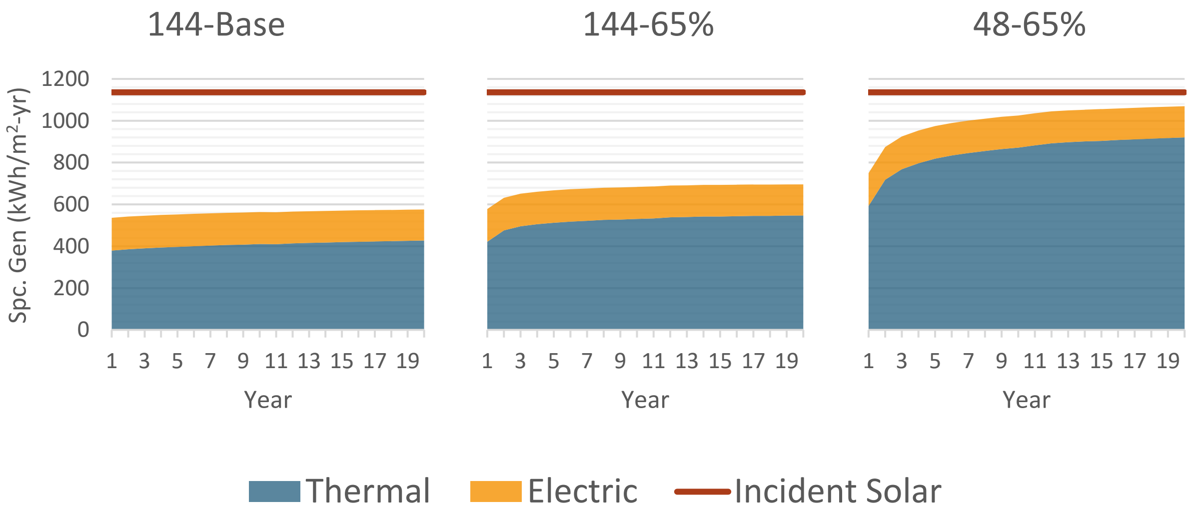

Figure 36 – Specific annual solar generation for three cases

It is well known that PV cells are less efficient when they operate at elevated temperatures, losing about 5% efficiency with every 10K increase in temperature. This is part of the motivation in cooling them in a PVT collector, however Sweden is already a cold climate where the cells rarely reach high temperatures. Figure 37 shows the specific production of a PV array (in kWh_{el}/kW_p, a different metric than solar thermal) with only air-cooling, and the 48 collector PVT array. The PVT array produces about 2% more electricity each year, nearly all of which is gained during the summer months. This amounts to a few hundred kilowatt-hours over the year and is about the same amount as the circulation pump consumes, basically making the net electrical energy cost of capturing solar heat free. There are moments in midday when the electrical efficiency may be 15% greater with PVT, however these are usually short lived and make little difference in the annual system performance. Only one PVT system is shown here because the differences between them is negligible. The reduction in output over time is due to the degradation of the PV cells.

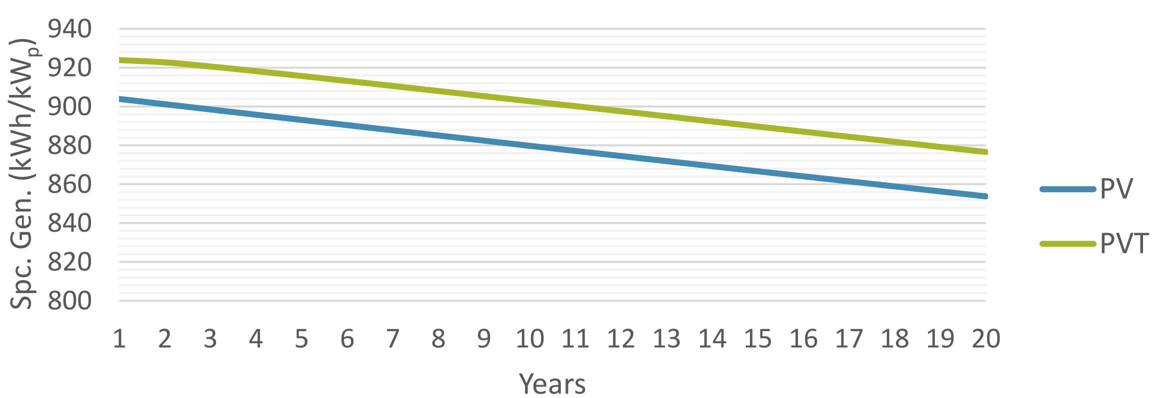

Figure 37 – Comparison of PV and PVT electric generation

5.9 Sensitivity Analyses

Economic variables are typically highly uncertain, thus benefiting from a sensitivity analysis to identify the relationship between input prices and results. This section gives a brief look at two sensitivities to TLCC: discount rate and electricity price. Results are presented for the 65% scenario considering no PVT, 144 and 48 collector arrays, and are compared to district heating.

Discounting reduces the weighting of future costs, meaning that a higher discount rate reduces the perceived lifetime cost as shown in Figure 38. The systems with higher investment, such as those with PVT, have less of a reduction. District heating has no investment cost in this study, and therefore decreases the most rapidly. These results confirm that low interest rates in the marketplace are beneficial to expensive renewable energy systems.

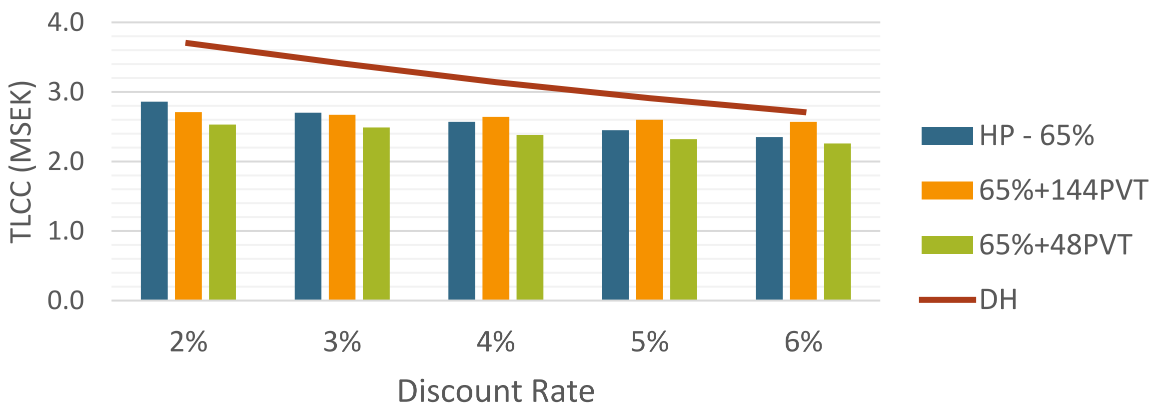

Figure 38 – TLCC sensitivity to discount rate

Electricity prices in the Nordics are relatively low due to the high fraction of hydropower, but also include a significant amount of taxes at the retail level. Currently, prices are near historic lows and have been notably higher in the past. The price of electricity is a key factor in heat pump's ability to compete with district heating, and as Figure 39 shows could make them uncompetitive if prices were to rise too much.

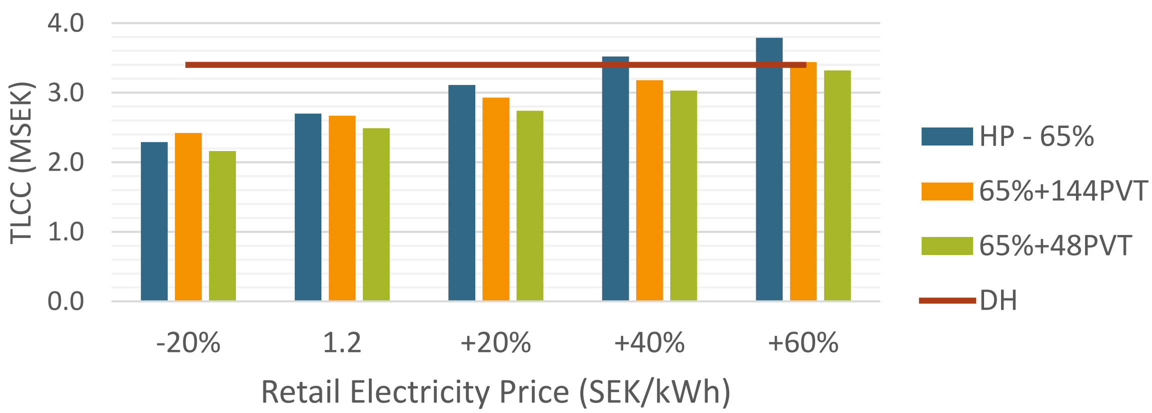

Figure 39 – TLCC sensitivity to retail electricity price

5.10 External KPI

This section presents performance indicators at the fourth and outermost boundary level, where the building's energy system combines with factors outside its walls. KPI considering Stockholm's and Sweden's energy systems are given: primary renewable energy fraction, primary energy demand, and CO_2 emissions. A comparison is made with district heating since it is the current standard for MFH. These results are limited to the heating system only and does not include electricity used in the apartments.

Renewable energy fraction, shown in Figure 40, is given for the combined borehole scenarios. District heating values are taken from the Stockholm region and electricity comes from the Swedish national grid. Since the benefit of the PVT system is to have shorter boreholes rather than higher efficiency, the renewable fraction is only improved by the PV cells. This is nearly the same in all cases except for the 65% scenario, where the electricity demand is reduced more significantly by PVT in the winter. The results also show that a standard heat pump has a lower renewable fraction than district heating in Stockholm, but that PV pushes it above. This may be in contrast to other sources, but when the primary energy is considered, not just delivered electricity, the fractions are much lower. The differences between heat pumps and district heating here are relatively minor though, and DH renewable fraction can easily increase with more biomass as in many other Swedish cities with closer connection to the forestry industry.

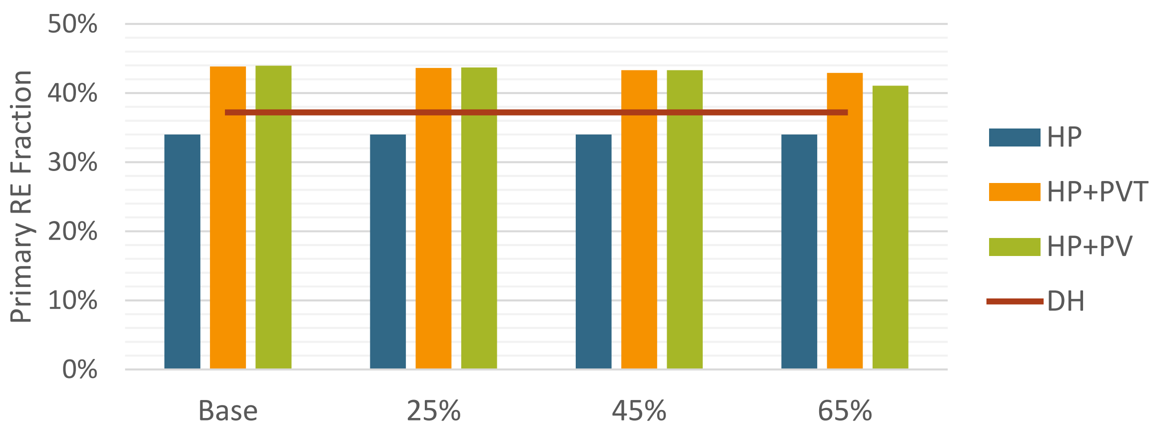

Figure 40 – Primary renewable energy fraction of heat pumps and district heating

A larger difference is found in the total primary energy used by each heating technology, shown in Figure 41, where heat pumps require less than half of the energy as district heating. Between heat pump cases, the shorter boreholes make the GSHP systems less efficient, but increase is less when PVT is added. Comparing the PVT+GSHP systems, the 65% system uses 12% more electricity than the baseline, confirming that a traditional borehole field is preferred if available. However, if the space is not available and the building is currently using district heating, then the switch to a GSHP will have a notable reduction in primary energy demand.

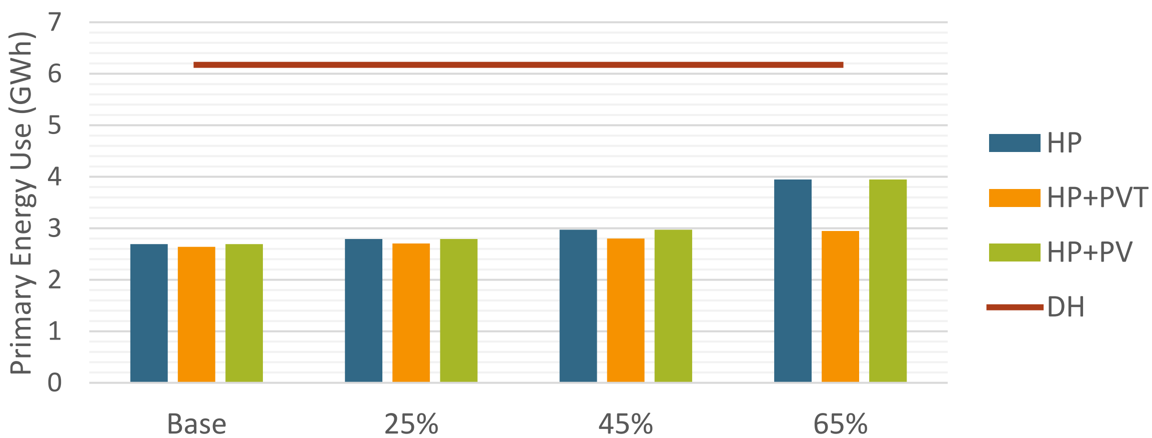

Figure 41 – 20 year primary energy usage in heat pumps and district heating

The carbon dioxide emissions, shown in Figure 42, mirror Figure 41 in that more CO_2 is emitted by a less efficient heat pump. There is a more notable difference between the heat pumps and district heating, where the heat pumps emit approximately 90% less CO_2. If PVT systems can enable more heat pumps to be installed in MFH, then a reduction in emissions from the building sector could be expected. It should be noted that this figure does not include global warming potential of refrigerant leakage or embedded energy, only the emissions from operational energy usage.

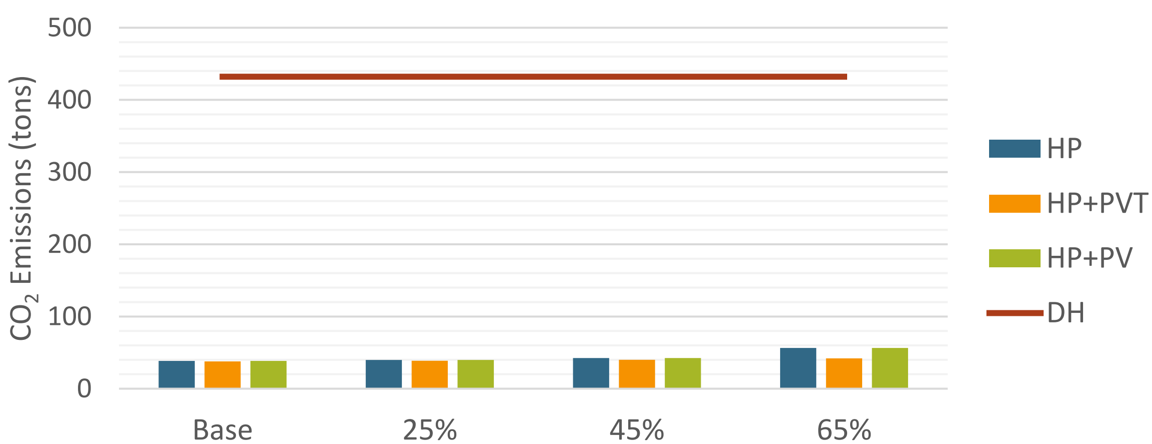

Figure 42 – 20 year CO_2 emissions from heat pumps and district heating

6 Metered Installations

There are a small number of PVT plus GSHP systems in Sweden, several which are pilot projects installed by project partner Solhybrid i Småland. Three are installed in single-family houses and one is a municipal housing complex. It had been planned that data from at least one installation, the housing complex, could be used for testing and model validation. However the housing complex also includes a commercial kitchen with a unique free cooling component that would makes comparison with a typical MFH impossible. Likewise, the single-family house designs are significantly different from how a MFH would be designed.

This shortcoming was turned into an opportunity by another project partner, Skånska Energilösningar, who had a new heat pump installation that would be a good candidate for PVT. The site at Flyinge Kungsgård just north of Lund, was converting the gas furnace based space heating in the main competition arena to a GSHP. The limited space and difficult drilling conditions caused the borehole field to be shorter and with less spacing between holes than should normally be designed. At one point free cooling was suggest in part to regenerate the boreholes, and this is when PVT was proposed. This opportunity has been used to create a comprehensively monitored test site that will provide valuable date for operations testing and model validation. The objective within this project for metering and data analysis then shifted from existing installations to designing and installing a purpose built test site from scratch.

6.1 System Description

The GSHP system is used for space heating in the main competition arena at Flyinge Kungsgård (referred to as Flyinge). It uses a Thermia Mega XL variable speed heat pump with heat sourced from eight borehole heat exchangers and delivered to a 1000L hot water tank. The hot water is then circulated through a fan coil and warm air distributed through the arena. The borehole field has 10 m spacing in a 3 x 3 grid (one corner is missing) and most holes are 200 m deep. The loose soils in Skåne led to some holes being drilled shorter due to the extensive need for casing. The PVT array consists of 20 Solhybrid prototype modules, totally 32 m^2 and 5 kW_p of PV power.

To make the system as flexible as possible for testing, it is possible to make two configurations, shown in Figure 43. On the left is the heat exchanger method (HEX) that has been describe and simulated in chapters 4 and 5. On the right is the dual u-tube method, which delivers the PVT heat to the center borehole via a separate u-pipe from the heat pump. This method allows each circuit to operate independently, allows heat transfer to the secondary heat pump fluid in the borehole, and delivers excess heat directly to the ground. The system has been commissioned with the Dual U-Tube configuration with all of the connections necessary to switch to HEX.

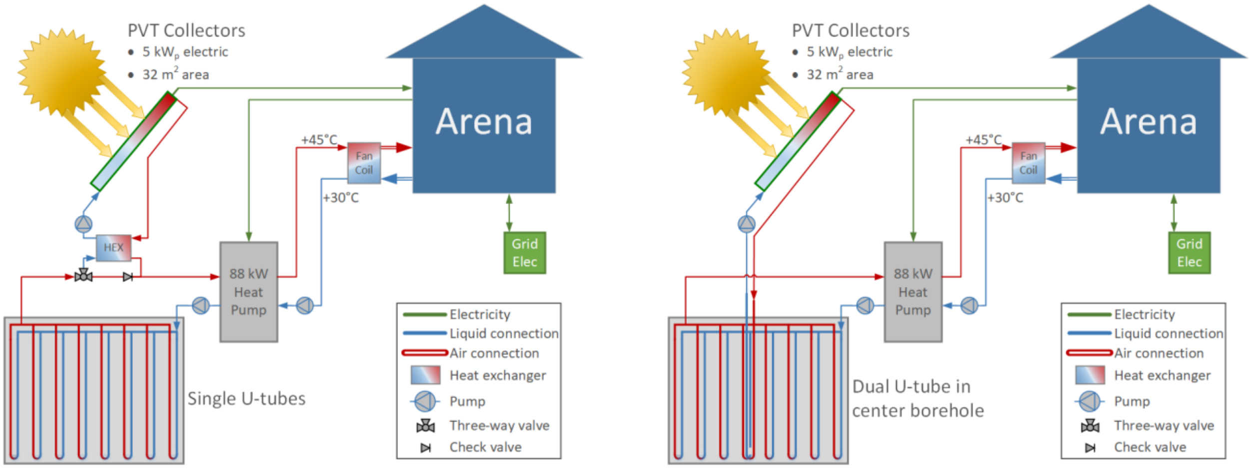

Figure 43 – HEX (left) and Dual U-Tube (right) configuration options at Flyinge test site

The PVT collectors are mounted on two roof surfaces, one facing west and the other south. The west collector array can be seen in Figure 44 with the south facing array on the roof around the corner. The photos in Figure 45 show the mechanical room shortly after the heat pump was installed (left), where the heat pump, tank, and air-handling unit are visible. The space underneath the air-handling unit is where the PVT and monitoring equipment are installed, shown on the right in Figure 45.

Figure 44 – Flyinge exterior with a view of the PVT collectors on the roof

Figure 45 – Flyinge mechanical room (left) and PVT plus monitoring equipment (right)

6.2 Monitoring

Flyinge is equipped with comprehensive monitoring throughout the PVT and GSHP system. Mounted directly above the PVT collectors is a Davis weather station that includes a solar radiation sensor, and captures data every minute. Thermal power meters are installed on the PVT collector array, source and sink side of the heat pump, and in four of the boreholes. These meters monitor flow rate and temperatures in their respective circuits. There are also separate temperature sensors monitoring inlet and outlet values directly at the PVT collector array. Electric power meters monitor PV generation, PVT circulation pump demand, and heat pump demand. The PVT circulation pump controller uses a simple dead band control strategy with a temperature sensor at the outlet of each array and one in the dual u-tube borehole. These temperatures and the signal from the controller are also recorded. A complete diagram of the monitoring equipment is given in Figure 46.

6.3 Future Work

The heat pump system was commissioned in early 2017 and the PVT system in early 2018. The monitoring equipment is collecting data, which is stored locally on a PC with remote access and backed up automatically locally and to a cloud server. In the absence of usable test data from existing PVT plus GSHP systems, this site was designed with the goal of enabling full systems model validation, flexible configuration and control testing for solar energy, and borehole temperature response. The Flyinge site provides multiple opportunities for empirical research that will be followed up in future research.

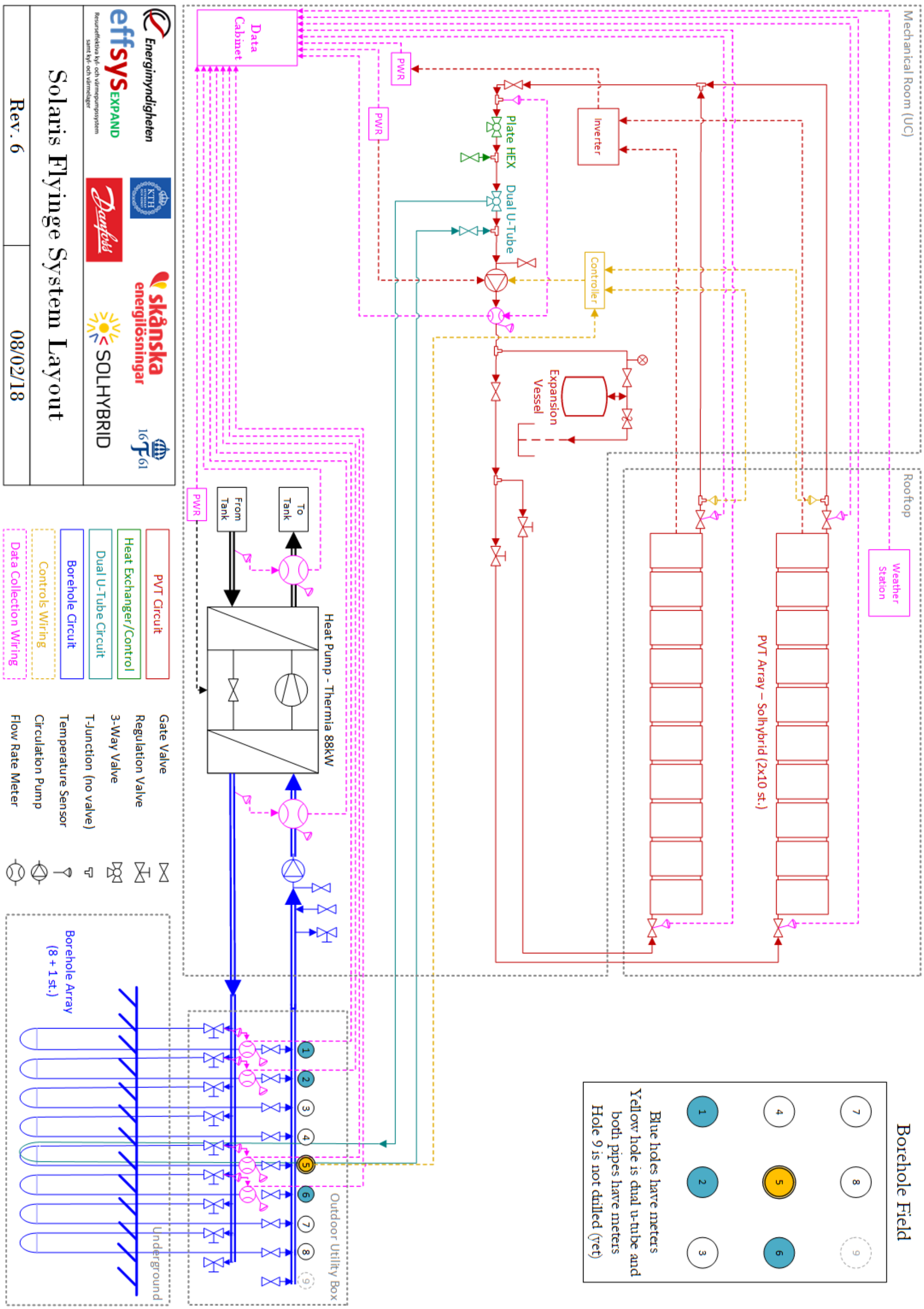

Figure 46 – Flyinge test site data monitoring diagram

7 Conclusions

Researchers and advocates of sustainable buildings are increasingly promoting heat pumps as part of an “electrify everything” strategy, where all loads use electricity and that electricity is generated using sustainable sources. In most countries, the concept generates minimal net benefit due to the high fraction of fossil fuels and carbon emissions of grid electricity. In the Nordics, electricity is supplied in predominantly from hydro and nuclear sources, making the switch from combustion based district heating to electric heat pumps more environmentally beneficial by dramatically reducing primary energy needs and CO_2 emissions.

This study has shown that PVT collectors can help unlock the Swedish multi-family house market for ground source heat pumps. Many MFH are built in dense urban areas where GSHP are not possible and air source heat pumps may be a noise disturbance. The integration of PVT into the heat source circuit can reduce the required borehole length and spacing for GSHP, making it possible to install them in MFH without adequate space for a conventionally sized borehole field. The energy and cost efficiency of the undersized field is less than a conventionally sized system, so if enough land area is available for drilling then a conventional borehole field is recommended.

In existing GSHP systems where the borehole length is undersized, PVT can rapidly boost efficiency and stabilize the ground temperatures to steady state in about 10 years. The benefits stem primarily from the reduction of backup boiler demands, which have a more significant impact on electricity demand than source fluid temperatures. The response is similar to the drilling of additional holes, however the PVT collectors can elicit the same response for less initial investment as drilling. They also have the benefit of producing electricity, which reduces operating costs over time, making PVT even more economically interesting than just the investment benefit over drilling.

The building and geology in this study are representative of typical Swedish conditions, however the results are just one case and require a south facing, unshaded rooftop. Specific boundary conditions should be simulated before applying these results to generic cases.

The form factor of modern PVT modules is the same as PV, which is experiencing rapid market growth in Sweden. There may be a significant potential for installers and equipment manufacturers to create PVT+GSHP packages that provide additional value for customers and society.

8 Discussion

The results presented in this study are generated using a large and complex systems model. There are several hundred inputs, most of which can or will be very different in specific real world cases. For example, ground water is not modeled here, which would have a considerable impact on the heat balance of the borehole field. There are also design choices that make this study simply representative of the potential for PVT rather than comprehensive, such as the building's orientation and construction. The number of potential variables that can be tested is far too great for a single study, and therefore this can be seen as a starting point for future work to identify more detailed building conditions and designs for Swedish PVT+GSHP solutions.

While individual components of the model are validated, one weak point in this study is the lack of a complete systems model validation. However, there are practical limitations to this given the rarity of this type of system in MFH. Every attempt has been made to use supported and reasonable boundary conditions and the results of the baseline (non-PVT system) has been checked with industry partners to ensure it is not unreasonably out of line from what would be expected in this type of installation. Due to the strictly theoretical nature of the study, the greatest value in these results lies in the relative performance changes rather than the absolute values.

The PVT integration, particularly those with smaller collector areas, is surprisingly effective. It must be highlighted that the PVT array only became cost effective in the system requiring heavy auxiliary boiler use. In this study, there is a backup heater to support the heat pump if loads are not being met, but the heat pump is not instructed to shut down until borehole fluid temperatures reach -10 °C. Many installers are likely to set a fault alarm higher than this to avoid the risk of damaging borehole collectors. The impact of this on SPF is significant (Bertram, 2014) and suggests that the PVT array may be cost effective in more conditions than those simulated here. Warmer fault temperatures would also necessitate larger PVT arrays, as the smallest array shown here was able to lift the borehole temps to only just above the fault level.

There has been a general consensus with previous solar heat pump studies that the solar heat should be used first in the building and second to regenerate (Hadorn, 2015). This applies mostly to systems with adequate length boreholes, however several studies have found that when the boreholes are undersized or are densely packed that regeneration is a better strategy (Bertram, 2014; Bertram et al., 2012; Kjellsson, 2009; Reda, 2015). While a direct-to-building configuration is not presented in this study, the results confirm that an undersized borehole application is effective in both energy and cost. A specific recommendation on length reduction cannot be made since there are many variables that affect the optimal point: building load, ground thermal properties, available roof area, energy and drilling costs, etc. Comparing this study to previous work, Emmi et al. (2015) found that an 80% length reduction in a MFH is possible in Stockholm using glazed solar thermal collectors, but only recommended a 50% reduction due to excessively high ground collector temperatures. In a German study, Bertram (2014) suggested a 20%

length reduction using glazed solar collectors, however this was in a SFH with a single borehole. So while the system design in this study is quite different from these other examples, the potential for borehole reduction has been noted elsewhere. A notable distinction of this study is the inclusion of an economic analysis, which highlighted that a traditionally sized borehole field with a PV array is still the most energy and cost efficient option. A reduced borehole length with PVT should be reserved for MFH with limited land space.

The positive results in this study suggest there is a potential for PVT+GSHP in Swedish MFH. Theoretical potential and market potential are two different things, and there is value in taking a business perspective towards the system. A SWOT analysis (Strengths, Weaknesses, Opportunities, Threats) helps provide insights into the market potential of a business or technology. A brief qualitative analysis is presented here to provide a business viewpoint (equipment manufacturers and installers) towards the development of PVT+GSHP.

8.1 Strengths

One of the greatest strengths in this design is the ease of integration of the PVT collectors into the GSHP. There is no special or large tank(s) or heat pump controller needed. The only modification is a heat exchanger in the borehole circuit and some additional piping to route through the building. It is possible that better performance can be achieved with a more intelligent controller, which is recommended for future work, but the results here show that it has potential even with a simple solar control strategy.

The PVT modules used here, and most on the market today, are unglazed and look like PV modules once they are mounted on the building. This is a strength simply because PV is popular and has a growing market in Sweden and the world (IEA-PVPS, 2017). There has been a lot of positive research on solar heat pumps using solar thermal collectors, however the ST market in Europe is waning due to competition from PV (Weiss and Spörk-Dür, 2018). In Sweden, the ST market has all but disappeared while PV continues to grow 50% per year. This is in part due to the generous subsidies for PV, but also because ST cannot compete with low price Swedish electricity and heat pumps. By presenting PVT as “a PV system that also captures heat”, customers can think of it as a PV system, which is already positive, but with a performance enhancement.

8.2 Weaknesses

While PVT can look like PV, it does still require much of the additional hardware and installation effort of an ST system, which has a much higher system cost. First, adding the thermal collector to the PV modules adds approximately 200% to the price. The fixed costs of the thermal system installation are also quite high due to the plumbing and commissioning. Even though the PVT costs are partially offset by the reduced need for boreholes, high initial costs are a barrier to widespread market adoption. There are many years of experience in solar thermal installations and the cost remains high, so it is unlikely to be dramatically reduced. For the GSHP application, where working temperatures are relatively low, the collector cost could be reduced by using a polymer heat exchanger, which some companies are already exploring.

8.3 Opportunities

As was discussed in the results, the greatest current opportunity for PVT+GSHP systems is in the retrofitting/replacement of existing GSHP systems. Several examples of MFH with undersized borehole fields were reviewed during this project, and it is possible that a PVT solution could have been a lower cost solution with less disturbance to the property. While not covered explicitly here, the SFH market in Sweden is starting to be dominated by replacements (EHPA, 2016), which likely have boreholes that are too short for the higher efficiency replacement. If heat pump manufacturers can offer “PVT ready” systems, it could add significant value for installers and customers.

The next opportunity lies in MFH that otherwise would not be able to install a GSHP. There are many other possible borehole configurations to test, but a reduction in length of 65% while also being packed together much tighter opens up a much larger MFH market than exists today.

8.4 Threats

There are several threats to the success of PVT plus GSHP systems; implementation, price uncertainty, and policies. There is relatively little experience in the implementation of PVT heat pumps in Sweden, and while the results from this study are promising, there is still a need for greater understanding of system behavior in the real world. It is possible the technology could underperform as compared to the model. The sensitivity of the system to poor design or control is also not well understood, and so additional report from existing pilot projects and reporting on future installations are needed to help build the knowledge base.

As the sensitivity results show, an increase in electricity prices is generally a negative for the heat pump market. Conversely, higher prices are positive for solar PV, and by extension PVT, which help reduce the pain of the price increases since the cost of electricity from PV is lower than the retail grid. It is not only the electricity prices, but their relation to district heating prices that is important. If DH prices come down, and electricity prices go up, the motive for MFH to switch to heat pumps is reduced. In the face of a market threat from heat pumps, it is possible district heating providers may try to alter their pricing or product offerings in order to compete. At the moment this threat is low due to the lack of economic and environmental alternatives, but solar heat pumps could change this and it is necessary to assume that DH companies would not sit idly if they start losing significant market share.

Perhaps more significant than market forces at the moment are government forces in the form of solar energy subsidies. PVT currently qualifies for a 30% investment rebate, which makes a significant difference in the TLCC since it occurs at the beginning of the system’s lifetime. The subsidy will not continue indefinitely, placing even more pressure on the need to reduce collector and system costs.

9 Project Outcomes and Impact

The broad objective of this project was to identify the technical and economic potential of solar PVT integrated with GSHP systems in multi-family houses, considering the following four questions:

- What is the improvement of adding PVT to a standard GSHP system?
- Can the borehole length be reduced if PVT supplements the ground source?
- Can PVT replace supplemental drilling in undersized borehole fields?
- How much, if any, is the renewable fraction of buildings increased?

The results and conclusions show that this has been accomplished primarily through complex systems simulation. Below are answers to the first three research questions with reference to the section(s) with relevant results:

- PVT has minimal benefit for adequately sized borehole fields and is more expensive than a PV-only installation (5.3, 5.5, 5.6).
- PVT can support reduced borehole lengths by 65% and is economically competitive in cases where auxiliary boiler use is high (5.4, 5.6).
- PVT is an economically viable alternative to drilling in undersized borehole fields (5.7).

The renewable fraction of buildings is found to be marginally improved with PVT since district heating already has a high renewable fraction (many cities have higher use of biomass than Stockholm) and PV provides almost all of the improvement. However, the reduction of primary energy and carbon dioxide emissions from heat pumps mean that expanding their use in the building stock has a strongly positive environmental impact and PVT collectors can be a catalyst for expansion. The highlight of renewable fraction at the beginning of the project should have been focused on overall sustainability goals and not just a single KPI.

To complement the theoretical results, practical aspects of PVT plus GSHP have also been considered by working closely with project partners. Solhybrid i Småland's pilot PVT plus GSHP system at Olofsgården assisted living community in Åseda has been operating successfully for three years. While it was not planned in the original application, Skånska Energilösningar (previously Geobattery) identified a test site at Flyinge Kungsgård that was an ideal application for PVT due to the undersized borehole field. Monitoring began too late in the project to be used, but the site is expected to provide valuable data for future research projects. Also, with the installation being on the main competition arena, the site has a high visibility to the public, providing an education opportunity about renewable energy. The installation of the PVT system was relatively easy to add to the original plan for the GSHP, highlighting ease of integration, and the data collection will greatly benefit future research projects.

During the project, results dissemination has been made at multiple levels and is achieving good impact in industry and academia. With project partners results have been presented primarily through private meetings, held annually as a whole group and every 3-6 months with individual partners. Public presentations have been given at well-attended workshop hosted by KTH, shown in Figure 47, and two Svenska Kyl- och Värmepumpardagar. The strong public interest in solar energy has attracted outside attention to the project. The Kyla+ article early on brought in a BRF from Östhammar with an undersized borehole field, much like original partner BRF Moranvikan had before they drilled additional holes (before the project). On an academic level, presentations and publications have been made at two international conferences, and one journal article has been published. Systems modeling challenges has slowed further publication, but two more journal articles will be submitted in 2018, two more conference papers have already been accepted, and one more abstract has been submitted. Two master's thesis and one PhD thesis will also be published as a result of the project.

Figure 47 – KTH Heat Pump workshop on June 1, 2018

The positive results found during this research has motivated the project partners to continue exploring PVT plus GSHP solutions: Thermia would like to learn more about detailed plumbing strategies, Solhybrid would like to get more feedback on PVT design and controls, and Skånska Energilösningar will continue to support the Flyinge test site and has proposed building others. Domestically, the PVT plus GSHP solution has the potential to save money for building owners and reduce environmental impact. Internationally, it combines a high growth technology (solar energy) with one Sweden already has a leadership role in (ground source heat pumps), making it a good strategic candidate for Swedish industry and export.

10 Future Work

When performing complex systems analysis in a relatively new design, it is difficult to describe the system comprehensively in a single study. The hydraulic models in these results are somewhat simplified, particularly since fluid temperatures reach levels where viscosity increases may influence pumping power. A more detailed analysis considering dynamic fluid properties, pumping power, valve configurations, and heat exchanger designs is needed to further optimize the system concept.

In the original project planning, measured data from existing an existing PVT+GSHP system was expected for model verification. The unique design of that system made it inappropriate for use in this project and instead a PVT plus GSHP installation was built with a KTH designed monitoring system. The comprehensive monitoring and flexible configurations make the site ideal for sub-system or whole-system model validation. Data is currently being collected and a new research project is needed to for processing, experimentation, and modeling of the test site for validation.

A considerable amount of effort was placed into identifying a borehole model that would be practical for the objectives of this study, however the TRNSYS model used here was not developed for this application and could be a source of error. Thermal interaction between boreholes is an active research field (Monzó, 2018) and the integration of PVT collectors would be good motivation to do a study using more powerful (e.g. finite volume/element numerical) models. The results of that study could help confirm the results seen in Type 557 or motivate the need for an alternative.

The addition of PVT collectors to undersized boreholes already in operation is the most promising application found in this study. The single-family house market is much more mature and moving into a period of renovation. A PVT+HP product could have a significant impact on efficiency of new systems, and a dedicated study to Swedish SFH is needed to quantify those benefits.

While the total lifecycle costs between systems is not dramatically different in these results, the investment cost of PVT collectors is notably higher than PV systems. There is a need to reduce the cost of both PVT collectors and the installation, particularly if investment subsidies are reduced. The series connected GSHP system results in considerably lower operating temperatures than what most PVT or thermal collectors are designed for, making it possible to use low-cost polymers. Development of lower-cost, GSHP specific PVT designs are recommended.

11 References

Acuña, J., 2013. Distributed thermal response tests – New insights on U-pipe and Coaxial heat exchangers in groundwater-filled boreholes. KTH Royal Institute of Technology.

Andrews, J.W., 1981. Ground coupled solar heat pumps: Analysis of four options, in: Amercian Society of Mechanical Engineers (Ed.), 4th ASME Solar Energy Division Conference. Amercian Society of Mechanical Engineers, Reno, Nevada.

Baetschmann, M., Leibundgut, H., 2012. LowEx Solar Building System: Integration of PV/T Collectors into Low Exergy Building Systems. Energy Procedia 30, 1052–1059. doi:10.1016/j.egypro.2012.11.118

Bertram, E., 2014. Solar Assisted Heat Pump Systems with Ground Heat Exchanger – Simulation Studies. Energy Procedia 48, 505–514. doi:10.1016/j.egypro.2014.02.060

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. doi:10.1016/j.egypro.2012.11.049

Bertram, E., Glembin, J., Scheuren, J., Rockendorf, G., 2010. Condensation heat gains on unglazed solar collectors in heat pump systems, Proceedings of the EuroSun 2010 Conference. Graz, Austria.

Bertram, E., Stegmann, M., Rockendorf, G., 2011. Heat pump systems with borehole heat exchanger and unglazed PVT collector, in: ISES Solar World Congress. Kassel, Germany, pp. 1170–1179.

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.

Buker, M.S., Riffat, S.B., 2016. Solar assisted heat pump systems for low temperature water heating applications: A systematic review. Renew. Sustain. Energy Rev. 55, 399–413. doi:10.1016/j.rser.2015.10.157

Bunea, M., Eicher, S., Hildbrand, C., Bony, J., 2012. Performance of solar collectors under low temperature conditions: Measurements and simulations results, in: Eurosun 2012 - ISES-Europe Solar Conference. Rijeka, Croatia.

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. doi:10.1016/j.apenergy.2014.04.075

Casetta, D., 2012. Implementation and validation of a Ground Source Heat Pump programs model in Improving landfill monitoring MATLAB. Chalmers University of Technology.

Dalenbäck, J.-O., 1990. Central Solar Heating Plants with Seasonal Storage - Status

Report (D14:1990). IEA Solar Heating and Cooling Programme - Task VII.

De Rosa, M., Ruiz-Calvo, F., Corberán, J.M., Montagud, C., Tagliafico, L.A., 2014. Borehole modelling: A comparison between a steady-state model and a novel dynamic model in a real ON/OFF GSHP operation. J. Phys. Conf. Ser. 547. doi:10.1088/1742-6596/547/1/012008

EHPA, 2016. European Heat Pump Market and Statistics Report 2016. 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. doi:10.1016/j.enconman.2015.10.016

Energi Företagen Sverige, 2017. Miljövärdering av fjärrvärme [WWW Document]. URL https://www.energiforetagen.se/statistik/fjarrvarmestatistik/miljovardering-av-fjarrvarme/

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. doi:10.1016/0038-092X(79)90190-7

Freeman, T., Mitchell, J., Audit, T., 1979. Performance of combined solar-heat pump systems. Sol. Energy 22, 125–135.

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

Häckel, B., Pfosser, S., Tränkler, T., 2017. Explaining the energy efficiency gap - Expected Utility Theory versus Cumulative Prospect Theory. Energy Policy 111, 414–426. doi:10.1016/j.enpol.2017.09.026

Hadorn, J.-C. (Editor), 2015. Solar and Heat Pump Systems for Residential Buildings, First. ed. Ernst & Sohn GmbH & Co., Berlin.

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. doi:10.1016/j.egypro.2012.11.071

Haller, M.Y., Carbonell, D., Mojic, I., Winteler, C., Bertram, E., Bunea, M., Lerch, W., Ochs, F., 2014. Solar and heat pump systems - summary of simulation results of the IEA SHC task 44/HPP annex 38, in: 11th IEA Heat Pump Conference. Montreal, pp. 1–12.

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, pp. 1–10.

Haller, M.Y., Perers, B., Bales, C., Paavilainen, J., Dalibard, A., Fischer, S., Bertram, E., 2012. TRNSYS Type 832 v5.00, Dynamic Collector Model by Bengt Perers: Updated Input-Output Reference.

Heier, J., Bales, C., Sotnikov, A., Ponomarova, G., 2011. Evaluation of a high temperature solar thermal seasonal borehole storage, 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.

Hirth, L., 2016. What caused the drop in European electricity prices? A factor decomposition analysis. USAEE Work. Pap. 16, 143–158. doi:10.5547/01956574.39.1.lhir

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. doi:10.1155/2014/808509

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.

IEA-PVPS, 2017. Trends 2017 in Photovoltaic Applications (T1-32:2017).

Kamel, R.S., Fung, A.S., Dash, P.R.H., 2015. Solar systems and their integration with heat pumps: A review. Energy Build. 87, 395–412. doi:10.1016/j.enbuild.2014.11.030

Kjellsson, E., 2009. Solar Collectors Combined with Ground-Source Heat Pumps in Dwellings. Lund University.

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. doi:10.1016/j.energy.2009.04.011

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

Kummert, M., Bernier, M., 2008. Sub-hourly simulation of residential ground coupled heat pump systems. Build. Serv. Eng. Res. Technol. 29, 27–44.

Lindahl, J., 2017. National Survey Report of PV Power Applications in Sweden 2016.

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. doi:10.1016/j.ijrefrig.2011.05.007

Mauthner, F., Herkel, S., 2016. IEA SHC Task 52, Technical Report Subtask C – Part C1.

Meggers, F., Ritter, V., Goffin, P., Baetschmann, M., Leibundgut, H., 2012. Low exergy building systems implementation. Energy 41, 48–55. doi:10.1016/j.energy.2011.07.031

Michael, J.J., Iniyan, S., Goic, R., 2015. Flat plate solar photovoltaic – thermal (PV / T) systems : A reference guide. Renew. Sustain. Energy Rev. 51, 62–88. doi:10.1016/j.rser.2015.06.022

Monzó, P., 2018. Modelling and monitoring thermal response of the ground in borehole fields.

Moro, A., Lonza, L., 2017. Electricity carbon intensity in European Member States: Impacts on GHG emissions of electric vehicles. Transp. Res. Part D Transp.

Environ. 0–1. doi:10.1016/j.trd.2017.07.012

Nord Pool Spot, 2018. Elspot Day-Ahead Prices [WWW Document]. URL www.nordpoolspot.com (accessed 1.20.18).

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.

Pahud, D., 1993. Etude du Centre Industriel et Artisanal Marcinhès à Meyrin (GE). Group de Physique Appliquée et Centre Universitaire d'Etude des Problèmes de L'Energie de l'Universitè de Genève.

Palm, J., 2018. Household installation of solar panels – Motives and barriers in a 10-year perspective. Energy Policy 113, 1–8. doi:10.1016/j.enpol.2017.10.047

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. doi:10.1016/j.renene.2014.07.052

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. doi:10.1016/j.rser.2017.07.041

Pressiani, M., 2016. Photovoltaic/thermal hybrid solar collectors: TRNSYS analysis and possible improvements. Politecnico Milano.

Reda, F., 2015. Long term performance of different SAGSHP solutions for residential energy supply in Finland. Appl. Energy 144, 31–50. doi:10.1016/j.apenergy.2015.01.059

Remund, J., Kunz, S., 2018. Meteonorm 7.2.

REN21, 2018. Renewables 2018 Global Status Report.

Riffat, S.B., Cuce, E., 2011. A review on hybrid photovoltaic/thermal collectors and systems. Int. J. Low-Carbon Technol. 6, 212–241. doi:10.1093/ijlct/ctr016

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

Ruschenburg, J., Herkel, S., Henning, H.-M., 2013. A statistical analysis on market-available solar thermal heat pump systems. Sol. Energy 95, 79–89. doi:10.1016/j.solener.2013.06.005

Salom, J., Widén, J., Candanedo, J., Lindberg, K.B., 2014. Analysis of grid interaction indicators in net zero-energy buildings with sub-hourly collected data. Adv. Build. Energy Res. 136, 1–18. doi:10.1080/17512549.2014.941006

Sommerfeldt, N., Madani, H., 2017. Revisiting the techno-economic analysis process for building-mounted, grid-connected solar photovoltaic systems: Part one - Review. Renew. Sustain. Energy Rev. 74, 1379–1393. doi:10.1016/j.rser.2016.11.232

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.

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 Dahbi.

Spets, K., 2012. TABULA Webtool [WWW Document]. URL http://webtool.building-typology.eu (accessed 5.31.15).

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.

Statsitics Sweden, 2013. Yearbook of Housing and Building Statistics 2012. Stockholm.

Stegmann, M., Bertram, E., Rockendorf, G., Janßen, S., 2011. Model of an unglazed photovoltaic thermal collector based on standard test procedures, in: Proc. of the ISES Solar World Congress 2011. Kassel, Germany.

Stockholm Exergi, 2018. Pris och avtal bostadsrättsföreningar [WWW Document]. URL https://www.stockholmexergi.se/fjarrvarme/bostadsrattsforeningar/priser/ (accessed 4.3.18).

Swedish Energy Agency, 2018. Energy in Sweden: Facts and Figures.

Threlkeld, J.L., 1953. Solar energy as a potential heat source for the heat pump (Phd Thesis). University of Minnesota.

Tyagi, V.V., Kaushik, S.C., Tyagi, S.K., 2012. Advancement in solar photovoltaic/thermal (PV/T) hybrid collector technology. Renew. Sustain. Energy Rev. 16, 1383–1398. doi:10.1016/j.rser.2011.12.013

V. Godefroy, C. Lecomte, M. Bernier, M.D. and M.A., 2016. Experimental validation of a thermal resistance and capacity model for geothermal boreholes. ASHRAE winter Conf.

Weiss, W., Spörk-Dür, M., 2018. Solar Heat Worldwide.

Widén, J., 2011. Correlations Between Large-Scale Solar and Wind Power in a Future Scenario for Sweden 2, 177–184.

Widén, J., Lundh, M., Vassileva, I., Dahlquist, E., Ellegård, K., Wäckelgård, E., 2009. Constructing load profiles for household electricity and hot water from time-use data—Modelling approach and validation. Energy Build. 41, 753–768. doi:10.1016/j.enbuild.2009.02.013

Widén, J., Wäckelgård, E., 2010. A high-resolution stochastic model of domestic activity patterns and electricity demand. Appl. Energy 87, 1880–1892. doi:10.1016/j.apenergy.2009.11.006

Yang, H., Cui, P., Fang, Z., 2010. Vertical-borehole ground-coupled heat pumps: A review of models and systems. Appl. Energy 87, 16–27. doi:10.1016/j.apenergy.2009.04.038

Zondag, H., 2008. Flat-plate PV-Thermal collectors and systems: A review. Renew.

Sustain. Energy Rev. 12, 891–959. doi:10.1016/j.rser.2005.12.012

12 Project's Scientific Publications

Poppi, S., Sommerfeldt, N., Bales, C., Madani, H., Lundqvist, P. 2018. Techno-economic review of solar heat pump systems for residential heating applications. *Renewable and Sustainable Energy Reviews*, Volume 81, Part 1, Pages 22-32.

Sommerfeldt N, Ollas P., 2017. Reverse engineering prototype solar PV/thermal collector properties from empirical data for use in TRNSYS Type 560. *Conference Proceedings of ISES Solar World Congress 2017*, Abu Dhabi, Oct 29 – Nov 2.

Sommerfeldt, N. and Madani, H., 2017. Integrating solar PVT collectors with GSHP in multi-family houses. *12th IEA Heat Pump Conference, HPT Annex 46 Workshop*, Rotterdam, Netherlands, May 15.

Sommerfeldt, N. and Madani, H., 2016. Review of solar PV/thermal plus ground source heat pump systems for European multi-family houses. *Proceedings of the ISES Eurosun Conference 2016*, Palma de Mallorca, Spain. October 11-14. doi: 10.18086/eurosun.2016.08.15

Forthcoming publications

Sommerfeldt, N. and Madani, H. A parametric study of PV/Thermal plus ground source heat pump systems for multi-family houses in heating dominated climates. To be submitted to the journal *Solar Energy* in summer 2018.

Sommerfeldt, N. and Madani, H., A system boundary framework for performance indicators in solar heat pump analysis. To be submitted to the journal *Energy and Buildings* in autumn 2018.

Sommerfeldt, N. and Madani, H. A techno-economic comparison between PV and PVT integrated ground source heat pumps for multi-family houses, accepted to the *ISES Eurosun 2018 conference*, Rapperswil, Switzerland, September 10-13.

Fischer, D., Juelch, V., Trebesch-Weber, J., Hollinger, R., Sommerfeldt, N. Influence of user-behaviour, electric vehicles and heating technology on the viability of PV projects in small and large multifamily houses, accepted to the *ISES Eurosun 2018 conference*, Rapperswil, Switzerland, September 10-13.

Razzetti E. 2018. Potential for seasonal electricity storage in borehole thermal energy stores with heat pumps. KTH MSc Thesis, to be completed August 2018.

Andersson M. 2018. PV versus ST – which is the best solar resource for heat pumps? KTH MSc Thesis, to be completed August 2018.

Sommerfeldt, N., 2019. Preliminary Title: Solar energy in Swedish buildings – A techno-economic analysis. KTH PhD Thesis.

13 Project's Popular Science Publications

Oral presentation, KTH Heat Pump Workshop, Stockholm, June 1, 2018.

Oral presentation, Effsys Expand forskardagar 2018, Tranås, April 17-18.

Oral/poster presentation, Svenska Kyl & Värmepumpardagen 2017, Stockholm, Oct 20.

Poster presentation, KTH Energy Dialogue 2016, Stockholm, Nov 24.

Poster presentation, Svenska Kyl & Värmepumpardagen 2016, Göteborg, Oct 21.

Oral presentation, Effsys Expand forskardagar 2016, Tranås, May 17-18.

Sommerfeldt N, Madani H, Palm B, Innovativ strategier för elproduktion och värmelagring för svenska flerfamiljshus. *Kyla och Värmepumpar*, 2016, Nr2, 42-45.