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REVIEW OF SOLAR PV/THERMAL PLUS GROUND SOURCE HEAT PUMP SYSTEMS FOR EUROPEAN MULTI-FAMILY HOUSES

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Abstract

The combination of photovoltaic-thermal (PVT) hybrid modules with ground source heat pumps (GSHP) has the potential to increase renewable fractions of heating, cooling and power generation in buildings. The concept benefits each component in the system; the solar collector can be more efficient; collected heat can be stored in the boreholes and recovered in both short and long term; and the elevated temperatures of the boreholes improves the efficiency of the heat pump. System optimization is challenging due to the number of possible configurations, options in component designs and system control, and the close interrelation of performance between components. This study presents several system configurations which are designed to be a balance of performance, practicality, and cost. The designs are based on a state-of-the-art literature review from multiple fields (solar collectors, heat pump controls, seasonal thermal storage, and solar assisted heat pumps) and consultations with heat pump and PVT collector manufacturers.

Keywords: Solar PV/thermal, Ground Source Heat Pump, Seasonal Thermal Storage, Systems Integration

1. Introduction

In light of environmental challenges, throughout Europe there is an increased interest in integrating solar power with the built environment. At the same time, heat pumps are often considered an environmentally sound method for producing heat or domestic hot water and are often part of low-energy or net zero energy building (NZEB) concepts (Cao et al., 2016). The combination of the two, known as a solar assisted heat pump (SAHP), has been investigated for decades (Andrews, 1981a; Freeman et al., 1979; Threlkeld, 1953) with the idea that the two technologies can complement each other and improve the system as a whole. Recently, research on the subject has accelerated as environmental and regulatory pressures to reduce energy demand in buildings increase.

SAHP systems are complex both in design and operation. For the heat pump, there are multiple potential heat sources (air, ground, water, aquifer, solar) and sinks for delivering space heating and domestic hot water (hot water tanks, traditional radiators, floor heating, combi-stores, etc.) that result in a multitude of design options. Likewise, solar collectors have several designs and configurations, such as thermal and/or photovoltaic, insulated (glazed) or not, and liquid or air based. The hydronic connection can be done in series, parallel, or both and can also include regeneration of a seasonal thermal store. All together, the options are quite broad.

The recently concluded IEA project on solar assisted heat pumps (Solar Heating and Cooling Task 44 / Heat Pump Program Annex 38, hereafter referred to as T44A38) resulted in a useful handbook for guiding engineers and researchers (Hardorn, 2015). While successful examples of most configurations could be found, the most promising solutions tended towards insulated (glazed) solar collectors working in parallel with the heat pump. At the same time, the best examples also tended to be the ones where components were specifically designed for a SAHP configuration and where the control strategy was well planned.

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The majority of the IEA project research, and the research on SAHP in general, has been done considering solar thermal collectors in single family houses (Haller et al., 2014). However, as noted in the handbook, photovoltaic/thermal (PVT) hybrid collectors are an interesting prospect that merit further investigation. The co-generation of heating, cooling, and electricity can produce more renewable energy per roof area than other solar solutions and will likely result in alternative control strategies to thermal-only systems (Dott et al., 2012). Multi-family houses (MFH) are often overlooked since 90% of European heat pumps are installed in single family houses (EHPA, 2015), even though 40% of Europeans live in multi-family houses (Eurostat, 2015). Space for heat sources, in particular ground sourced systems, is a common limitation for MFH which are often located in denser urban areas. Regenerating the ground with solar heat could make ground source heat pumps (GSHP) a possibility for more MFH with limited space (Reda, 2015).

A recently initiated research project at KTH Royal Institute of Technology aims to fill a research gap for PVT plus ground source heat pump (GSHP) systems in MFH (Sommerfeldt, 2016). As a first step in the project, this study's objective is to identify PVT+GSHP systems with a high probability of implementation through improved performance, ease of integration, and cost efficiency. This is done primarily through a state of the art review. However given the relative lack of examples for this type of system, guidance must be inferred from similar SAHP systems as well as reviewing the relevant literature of each component.

The application for this system is in heating dominated climates, therefore less inspiration is taken from systems with significant cooling loads given their different operating conditions. There is also considerable interest in the ability to store the excess of solar energy from the summer to the winter, which is made easier with the use of boreholes in the GSHP. Direct-expansion collectors, i.e. those which use the PVT as the heat pump evaporator, are not considered due to their relatively low technology readiness for commercial use, higher cost, and risk for environmental impact. The strengths, weaknesses, and motivations for each design will be presented and the study concludes with an outline of the future work planned for the chosen systems.

2. State-of-the-Art Review

The investigation of PVT+GSHP systems dates back to 1981, where series, parallel, and even ground regeneration were all considered (Andrews, 1981b). The conclusions were that in no case could PVT be economically justified over solar thermal due to the lower thermal efficiency and that all or most of the electricity is degraded into heat. It's important to note, however, that PV modules in 1981 had a typical efficiency of 6-10% and cost 25 USD/W_p. Today's commercial PV modules can routinely be 15% efficient for 0.75 USD/W_p (Fraunhofer ISE, 2015).This rapid decline in the cost of PV has significantly altered the approach designers take in adding solar generation to buildings, and could have a similar impact in the economics of SAHP systems.

Perhaps the most comprehensive review of SAHPs comes from Haller et al. (2014), which summarized the studies performed under T44A38 and was then adapted for the SAHP handbook. As previously mentioned, solar thermal systems working in parallel with heat pumps of any source typically have the best energy performance. This correlates with the types of product available on the market, which are dominated by glazed solar thermal collectors working in parallel with air or ground source heat pumps (Hardorn, 2015).

Kamel et al. (2015) reviewed the fundamentals of SAHP systems and corresponding collector designs with an objective of identifying promising systems for cold climates. Their focus was drawn towards PVT collectors, where it was found that most studies consider the collector as the evaporator (direct-expansion) and that most SAHP systems in cold climates use liquid as the working fluid. Buker and Riffat (2016) performed a review of SAHP for low temperature water heating with a focus on system classification and performance. They concluded that an optimal configuration cannot be identified for a given climate and application due to the wide range of possible system designs and methods for measuring performance, which is similar to the conclusions from T44A38. In light of this, they call for developing a standardized method for defining performance that can capture all designs.

The work performed under T44A38 is extremely helpful as a foundation, but additional input is necessary to guide system design. The remainder of this chapter will review specific PVT+GSHP systems, as well as relevant literature which can give important insights.

2.1. PVT + GSHP Systems

Although not as common as solar thermal systems, there have been several PVT+GSHP studies performed in recent years. To be certain, there are several other SAHP oriented studies which have included PVT collectors and are not considered here. This is due to the structures of those studies not lending themselves as well to be used for system design inspiration.

Bertram et al. (2011) studied the measurements from a single family house near Frankfurt, Germany with 39 m^2 of unglazed PVT collectors, a 12 kW GSHP, and 225m (3 x 75 m each) of borehole heat exchangers (BHE) for delivering space heating and DHW. Fig. 1 shows how the PVT collectors are connected in series to the BHE loop after the heat pump, thus delivering heat to the ground first and then to the evaporator. The measurements showed that heating demands were underestimated, thus resulting in an undersized BHE. TRNSYS simulations were used to estimate long term performance. After 20 years, the system without solar showed temperature degradation in the BHE whereas the solar equipped system did not, resulting in a 13% improvement in the seasonal performance factor (SPF) in year 20. Had the BHE been sized correctly however, the improvement would only be 6%. The electrical output of the PVT was also compared to uncooled PV modules on the same roof, which showed the PVT to produce 4% more electricity.

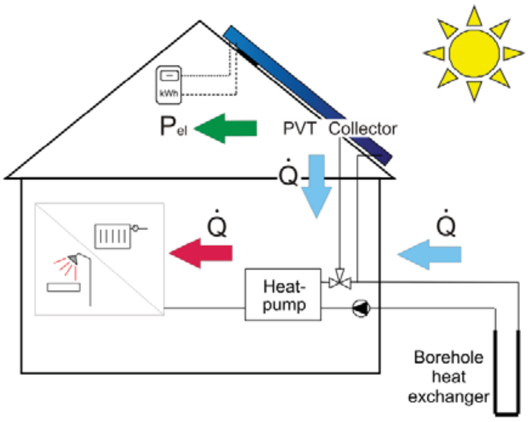

Fig. 1: PVT used to boost brine temperatures to the BHE (Bertram et al., 2011)

Another single family house in Montreal, Canada was simulated by Brischoux and Bernier (2016), shown in Fig. 2, which included a 140 m BHE with independent dual u-tube circuits, where one tube was connected to a 10 m^2 unglazed PVT array and the other to a 10 kW heat pump. The annual SPF only increased from 2.82 to 2.88. The mild performance increase was attributed to the unglazed collectors providing little benefit during the heating season, only having a single borehole (such that it could not act as a seasonal store), and that the BHE was appropriately sized. The cooled PV cells produced 7.7% more electricity than a traditional PV module. It is also worth noting that when the system boundaries are moved to include the PV production the SPF improves by 18%. This demonstrates the importance of defining relevant performance indicators, particularly when considering electrical and thermal co-generation.

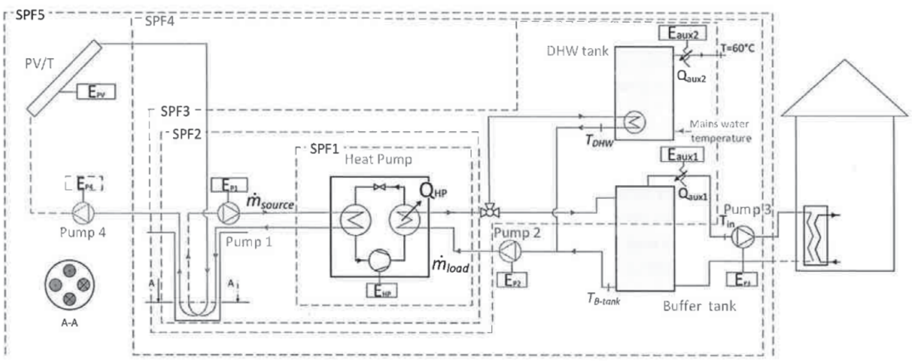

Fig. 2: PVT+GSHP concept using dual u-tubes in a single family house (Brischoux and Bernier, 2016)

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 where there are a set of 400 m boreholes for higher temperatures and a set of 200 m boreholes for lower temperatures. As shown in Fig. 3, the PVT collector heat can be used directly (in parallel) as a boost for the heat pump (in 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-lift heat pump. The simulations suggest that the average coefficient of performance (COP) could be near eight and an SPF during the heating season of six. This is about double what is typically expected in European GSHP systems and highlights the performance opportunities in taking a systems approach to building energy supply.

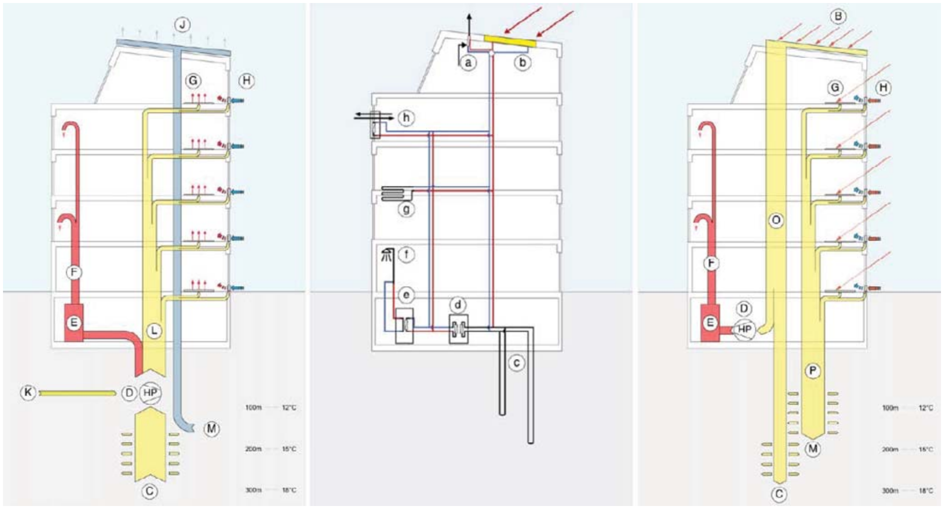

Fig. 3: Low exergy building concept configuration (center) in heating (left) and cooling modes (right) (Meggers et al., 2012)

2.2. PVT Collectors

PVT collectors come 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 plat collectors using a liquid working fluid are the most common, leaving the primary categorization in designs being between glazed and unglazed (Kamel et al., 2015). 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. In the case of unglazed collectors, there is also the choice to insulate the rear side of the panel.

The operating condition of the collector in conjunction with the GSHP is an important factor since temperatures can fall outside the typical operating conditions (Haller et al., 2012). In a series or 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 plat, 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 can 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 does need to be attended to.

2.3. Borehole Thermal Energy Storage

Several SAHP studies have shown that borehole regeneration using a single BHE is not energy efficient due to the heat dissipating too rapidly in the earth (Bertram, 2014; Bertram et al., 2012a, 2012b; Kjellsson et al., 2010). Additionally, appropriately sized boreholes (i.e. those which would operate successfully without solar regeneration) do not significantly benefit the heat pump's SPF (Kjellsson et al., 2010; Reda, 2015). In a MFH, it is usually expected that there will be multiple boreholes and thus there is the opportunity for creating a borehole thermal energy store (BTES). The design of these stores depends on many local factors, but some general design principles can be garnered from previous work.

Most solar BTES have been designed for low mean temperatures (10-40 °C), are usually supplied by glazed solar thermal collectors, and are used in combination with heat pumps (Dalenbäck, 1990; Rad and Fung, 2016). These systems are usually designed for a high solar fraction (50-90%) and often have relatively short boreholes (30-65 m) in order to give a compact volume for minimizing heat losses. Thermal stratification, which is done radially rather than vertically as in a hot water tank, is helpful for reducing losses and improving collector efficiency but can be difficult to achieve in the ground (Dalenbäck, 1990). Nordell and Hellström (2000) state that the heat losses, and thus the efficiency, of a BTES depend primarily on the size and shape of the store, average cycle temperature (more specifically, the temperature at the boundary of the store), and the thermal properties of the ground. The optimal BTES volume is highly dependent on size of the heating demand and the desired supply temperature, and the most efficient conditions are with large loads and low temperatures (Nordell, 1994; Pahud, 2000). It is suggested that only systems with high thermal loads (greater than 500 MWh/yr) can be built cost effectively (Dalenbäck, 1990; Pahud, 1996).

Drake Landing, a solar community of 52 single family houses in Alberta, Canada, uses flat plate collectors with a high temperature BTES that feeds directly to the buildings (McClenahan et al., 2006; Wong et al., 2006). The BTES is a 35,000 m^3 cylinder with 144, 35 m deep boreholes, 2.5 m spacing, six boreholes in series, a maximum storage temperature of 80 °C and was expected to have an efficiency of 40%. Measurements after five years show that the system is performing very close to the simulations and the BTES has an efficiency of 36% with an operating temperature range of 45-70 °C (Sibbitt et al., 2012).

Chapuis and Bernier (2009) examine a redesign of Drake Landing by lowering the store temperature to have a range of 10-16 °C and then combine with a GSHP. The solar collector area is reduced by 75% and the BTES volume enlarged nearly 300% by increasing the borehole spacing to 4.5 m. The result is greater collector efficiency (58% vs. 23%) due to the lower inlet temperatures and reduced heat losses by over 70%. This configuration does require significantly more auxiliary energy input (144 vs. 11 MWh) thus lowering the solar fraction to 78% from 98%. Unfortunately no economic comparison was performed to compare the savings from the solar collectors to the cost of the heat pump and electricity.

In addition to the BTES, Drake Landing uses short term thermal storage in the form of two hot water buffer tanks with a total volume of 240 m^3. A buffer tank is a common component in a solar thermal system, and Pohud (1996) identified that a BTES only becomes economically interesting when targeting solar fractions higher than 60%. Since some solar collectors are capable of producing heat faster than the BTES can absorb it, the buffer tanks can play an important role in the control of the system and increase the efficiency of the storage system as a whole. The size of the buffer tank is predominantly linked to the collector area, and less so with the heating load type and the size of the BTES (Pahud, 2000).

2.4. Control Strategies

With the increased deployment of solar PV in buildings, there has been a decrease in financial support schemes in many countries which make it less profitable to sell overproduced electricity to the grid. It can also be the case that high penetrations of PV in a power grid will erode the tariffs during these hours and thus reduce profitability. Therefore increasing self-consumption of solar generation using load shifting and/or energy storage is likely to be increasingly important in coming years (Luthander et al., 2015).

The use of a heat pump makes it possible to convert excess electricity into thermal energy for use in the building later on, and is a concept which has seen increasing research interest. Thygesen and Karlsson (2014) compared the cost effectiveness of storage using a hot water tank with a direct electric element for DHW to lead acid batteries. For an equivalent increase in self-consumption for both technologies (from 56% without storage to 88% with) the PV + battery system was found to cost double the PV + thermal storage. Thygesen and Karlsson (2016) went on to study a weather forecasting control for the GSHP, foregoing any direct electric storage. In this case self-consumption increased from 56% without predictive control to 63% with, however heat pump demand also increases due to additional running time called for by the controller.

Control systems, particularly with a complex hydronic configuration such as in a PVT+GSHP, can create difficult optimization problems. Salpakari and Lund (2016) presented a non-linear, cost-optimization algorithm considering appliance load shifting, battery storage, and GSHP control for a single family NZEB in Helsinki. The method was compared to a baseline building without controls and found to perform significantly better, with self-consumption increasing by as much as 30 percentage points and annual electricity costs decreasing 13-25%. A simpler rule based control algorithm was also tested and increased self-consumption, but usually resulted in higher annual costs due to increased storage losses and less efficient heat pump operation. The best performance was found with combined thermal and battery storage, however investments were not considered in a cost-benefit analysis. Storage was found to be more effective than load shifting towards improving PV self-consumption, which correlates with previous work (Widén et al., 2009).

Dar et al. (2014) compared several simple air source heat pump control strategies with PV in Oslo, considering; self-consumption maximization, electricity cost minimization, and grid import/export limitations. For a given system configuration, it was found that self-consumption could be improved by six percentage points and as much as 12 points if larger thermal stores were considered. Using spot price signals as a control input, the annual electricity cost could be reduced by up to 19%. These two objectives are currently at odds with each other, as the lowest electricity prices are currently during the night when there is no solar production. It was also shown that SPF of the heat pump was made worse in every case by 10-20% and that self-consumption by the heat pump is limited to about 35% without the use of seasonal storage.

3. Resulting System Configurations

Prior to the review, there were some design features which were planned to be a part of the system, such as the use of PVT modules, a GSHP, and a BTES. The method(s) in which these components would be connected and controlled however was unknown. In light of the review, it is clear that the complexity of the system makes objectively selecting a single best SAHP design difficult if not impossible. There are some overarching design principles which guide system design in this study to help identify a configuration. The focus is techno-economic, meaning that cost-optimized solutions are important, not only performance optimized. This places emphasis on relatively simple components and configurations, which has been previously highlighted as a design goal for future SAHP systems (Dalenbäck, 1990).

The design process can begin with the PVT collectors and the decision to use glazed versus unglazed. Glazed collectors can be more thermally efficient at the expense of electrical efficiency, but are likely to be restricted to the sink side of the heat pump (parallel configuration) due to the risk of condensation inside the collector from the low inlet temperatures of the BHE loop. Unglazed collectors have the advantage of acting as an air-to-water heat exchanger during periods of low irradiance, having lower cost due to less materials and can more easily integrate with PV systems (physically and aesthetically).

Having access to seasonal storage via the BTES is a major element in the design considerations. The elevated temperatures will supply the heat pump higher source temperatures, thus improving efficiency, but not without limits. The BTES core temperatures should be planned to be low enough such that it can continue to work with the heat pump during the summer when temperatures are highest. Integrating the collectors on the source side makes it easier to access the BTES for regeneration. It also has the advantage of being relatively easy to integrate into existing systems, as there would be no need to change the hydronic system between the heat pump and the building. A series configuration also pairs well with the unglazed PVT collectors, since much of the time outlet temperatures from the PVT will likely be too low to supply the building directly.

Considering the economic goals of the system and the inclusion of a seasonal BTES, a series/regenerative configuration is chosen for this project. Not using the solar energy directly may lead to a less energy or exergy efficient system (Haller and Frank, 2011), however it may be that the cost efficiency will be greater. The integration of the PVT collectors to the BHE loop remains an open question, and there are several possibilities to do this that are difficult to rank without more information. Therefore the following four design concepts will be simulated to determine performance and cost effectiveness; PVT-in-loop, heat exchanger, buffer tank, and dual u-tube.

The first concept, shown in Fig. 4 places the PVT collector in the same hydronic circuit as the connection between the heat pump and BHE, similar to the system presented by Bertram et al. (2011). The strengths of this configuration are its simplicity and low cost, where only one three-way and one check valve are required. The weaknesses include lack of control over flow rate or fluid properties, as the PVT collector is directly bound to the requirements of the heat pump and BHE.

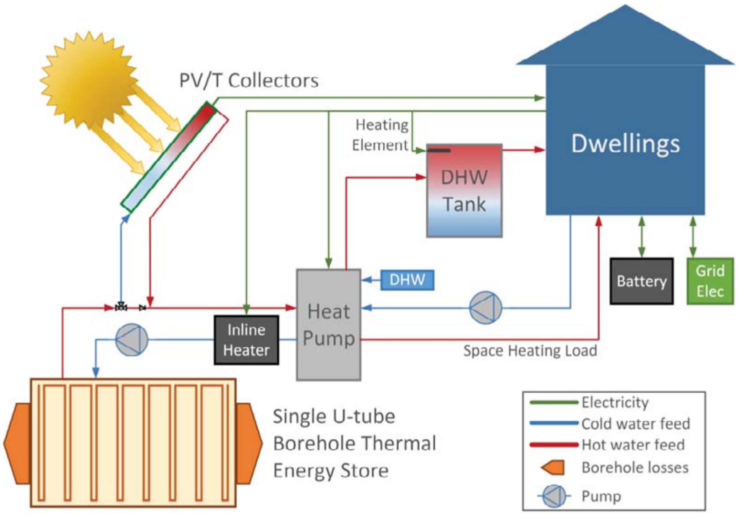

Fig. 4: Concept One using PVT in the BHE loop to boost incoming fluid temperature to the HP

There are two additional components that appear in every concept; batteries and an inline heater connected to the BTES. These allow the storage of electricity with the batteries being short term chemical storage and the BTES being long term thermal storage. While there may be large amounts of exergy destruction by heating the BTES with electricity, the heat is reducing the need for electricity from the heat pump in the winter thus acting as a method for storing electricity rather than simply converting it to heat. It can also test the cost efficiency of the BTES in comparison to selling electricity to the market.

Another consideration for all concepts is the connection point for the PVT collectors, which can go in either the supply or return lines from the BHE to the heat pump. Thermodynamically it would be the most logical to use the heat to boost the temperature supply into the heat pump, however they have a source temperature limit that could cause faults. Therefore a pre-study will need to be made to determine the appropriate connection point, which will then be used in all concepts.

Concept two uses a liquid-to-liquid heat exchanger to integrate the PVT collectors, as shown in Fig. 5. This configuration overcomes a weakness of concept one by allowing the PVT circuit flow rate to be controlled independently from the BHE circuit. It also allows for a separate working fluid, which may be important in later years when the BTES is fully charged and it's possible to reduce the fractions of antifreeze in the BHE circuit. The primary weaknesses are the additional cost of a heat exchanger and the higher pumping demands due to the additional pressure drop. From a practical standpoint, the integration of this concept into the physical system should be similar to concept one and does not require a prohibitive amount of space.

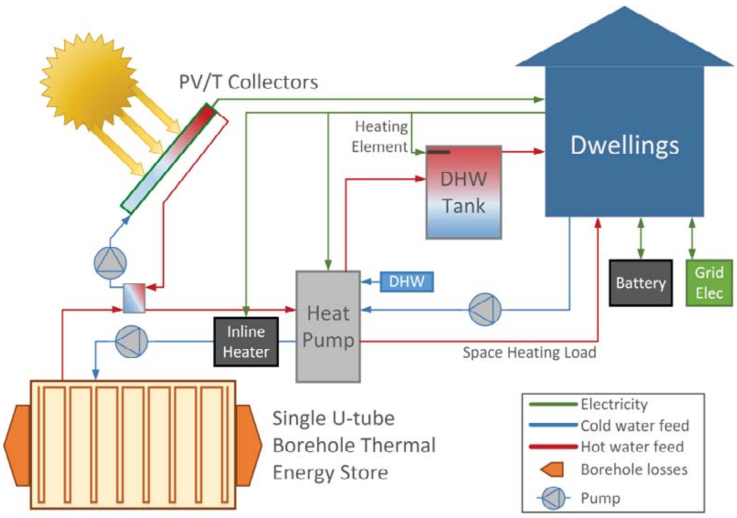

Fig. 5: Concept two using a liquid-to-liquid heat exchanger to boost incoming fluid temperatures to the HP

In concept three, the heat exchanger in concept two is replaced with a buffer tank as shown in Fig. 6. This concept's strength is that it could result in more efficient use of the solar heat by avoiding delivery to the BTES until there is an excess of solar energy beyond daily use, as recommended by Pahud (1996). The control of the buffer may require forecasting to decide when to release the heat into the BTES. This concept has the potential for improved control options over concept two, but has the weakness of the cost and space for space for the tank.

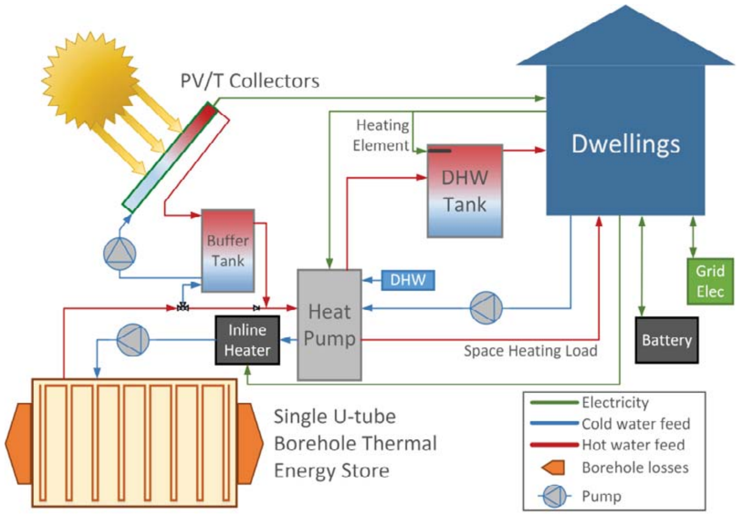

Fig. 6: Concept three using a storage tank to boost incoming fluid temperatures to the HP

Concept four, shown in Fig. 7, uses the BHE as the heat exchanger for the PVT collectors and the heat pump via a dual u-tube, similar to Brischoux and Bernier (2016). This configuration has the same strengths as concepts two and three, where independent working fluids and flow rates can be used. It also removes the need for valve control strategies since the circuits are completely separate and can be controlled independently. The greatest weakness for this concept is that it applies predominantly to new systems, since many existing systems only use a single u-tube and adding a second tube may be prohibitively expensive or impractical. There will also be high pumping losses in the PVT circuit since it includes the BTES as well.

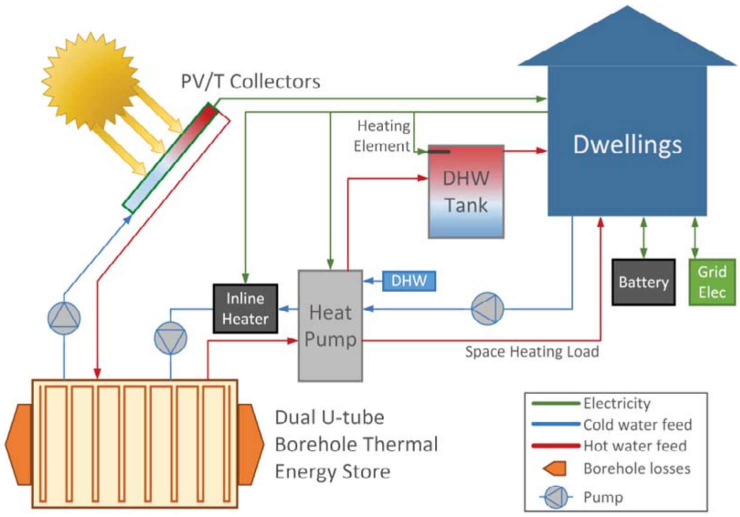

Fig. 7: Concept four using dual u-tubes as a heat exchanger and regeneration method

Recent market trends have seen new solar thermal system installations decline with the rise of solar PV, particularly on rooftops. PVT collectors have traditionally been used to create DHW directly but have never had a significant market share. In this application it is interesting to ask if the additional thermal energy collection justify the costs. Therefore a fifth concept, shown in Fig. 8, is considered which only uses PV collectors that are coupled to the BTES. This concept tests the marginal value of adding a thermal component to the PV collectors and the associated hydronic complexities. In this concept, the battery acts as short term storage, similar to a thermal buffer tank, while the BTES is used as long term seasonal storage.

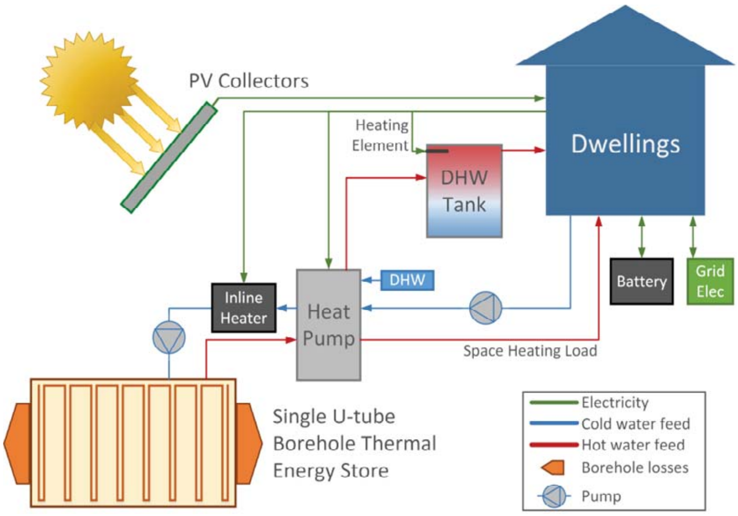

Fig. 8: Concept only considering PV and borehole regeneration

4. Discussion

A significant challenge when reviewing SAHP systems, particularly when comparing thermal to PV systems, is the lack of consistency between metrics used in studies (Buker and Riffat, 2016). Many authors use traditional key performance indicators (KPI) such as SPF, solar fraction, self-consumption, self-sufficiency, or renewable fraction, however the system boundaries are often not defined or do not capture the performance of the entire system as it relates to the owner. For example, if the indicator boundaries are limited to the heating system, the value of the PV generation to the rest of the building loads can be missed. The traditional indicators are still valuable to SAHP analysis, however care must be taken not to emphasize any particular one to the detriment of the others (Dar et al., 2014).

An extensive discussion surrounding the selection and use of KPI can be found in the SAHP handbook (Hardorn, 2015), and the top level systems definition of SPF is given by eq. 1. In the numerator is the total space (Q_{SH}) and domestic hot water (Q_{SH}) energy supplied to the building. The denominator includes the electricity used by the heat pump (E_{HP}), all auxiliary heaters ($E_{AUX,H}$), and all auxiliary pumps ($E_{AUX,P}$). One missing factor in this definition is electricity supplied from PV. In PV-HP literature there is often a focus on self-consumption and the definition for SPF is the same as in a non-solar HP, however as noted earlier, PV generation can make a significant improvement to SPF (Brischoux and Bernier, 2016).

$$SPF_{sys,grid} = \frac{\int Q_{SH} + Q_{DHW}}{\int [E_{HP} + \sum E_{AUX,H} + \sum E_{AUX,P}]} \qquad \text{(eq. 1)}$$

In a SAHP with PVT cogeneration, the handling of the electricity generation raises interesting questions about KPI. What fraction of PV generation should be applied to the heat pump? Is it necessary to make such a distinction in SPF? Are there other KPI (or combination of indicators) which would be more useful to the owner? Environmental or economic indicators can often be important to the purchaser of energy related equipment. In an economic KPI, it is important to capture the impact PV generation has on the entire building load and not limit it to the SAHP system. It is also necessary to capture all costs and benefits in order to make a fair comparison between options. Further research and careful consideration will be made towards the selection of KPI to ensure fair and relevant evaluation of the PVT+GSHP systems.

5. Summary and Future Work

Solar assisted heat pumps are complex in design, operation, and analysis. The review presented in this paper briefly captures some of the facets to be considered in the design of a PVT+GSHP system, including; collector design, borehole thermal energy storage, hydronic configurations and control strategies. The four PVT system concepts presented are focused on simplicity and practicality, and are of the series/regenerative configuration with various integration methods for the PVT into the BHE hydronic loop. They are designed primarily to maximize cost efficiency with the expectation that energy or exergy performance may not be as high as other designs. The marginal benefit of collecting heat from a PV array will also be tested by simulating a PV-only system which can also feed into the BTES.

The next steps in the project are to create system models in TRNSYS, finalize the remaining questions about system configuration, and identify appropriate ranges of component sizes. Input from component manufacturers for PVT collectors, heat pumps, and boreholes will be used to ensure that the practical limits of the components are respected and to identify opportunities for designs specific to this application. Care will be taken to ensure that most representative costs are used for the installed system, which is particularly important given the uniqueness of the concept. Control strategies will also be tested to optimize the use of the batteries, heat pump compressor speed, circulation pumps, etc. Effort will also go into defining meaningful KPI to evaluate and optimize systems that are relevant to the system owners. The primary area of application is in the Nordic region, therefore building construction, usage, and GSHP system designs will be taken from regional norms.

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