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PERFORMANCE OF HEAT PUMP ASSISTED BUILDING-INTEGRATED COMBINED PHOTOVOLTAIC THERMAL SOLAR COLLECTORS (BIPVT) IN COLD CLIMATE

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ABSTRACT

This paper evaluates configurations of indirect solar assisted heat pump systems with building-integrated combined photovoltaic thermal solar collectors (BiPVT) in cold climates. Energy simulations of these systems show that the system coefficient of performance (COP) can reach up to 5.6 for some selected configurations. Other configurations can provide a high solar fraction and a better collector efficiency (up to 43%) at the expense of lower COP.

A high COP and a better collector efficiency do not necessarily translate into a better investment because, factors like buying and selling prices of the heat and the electricity equally important. The economic performance of different configurations in a dynamic multi-dimensional comparison suggests that the relatively simple system without a heat pump can be a better overall choice for the cold climates.

INTRODUCTION

In this paper, we investigate how buildings can supplement their energy demand by using building-integrated combined photovoltaic thermal solar collectors (BiPVT) in conjunction with heat pumps by comparing the energy production potential and the economic performance of different configurations of BiPVT heat pump systems. The BiPVT collectors of concern for this study are unglazed liquid based BiPVT with a direct flow absorber design. The paper focus on an application of BiPVT for a 32-family multi-apartment building in Aarhus, Denmark. The system investigated can be generalised to all large systems operating under similar weather conditions.

A BiPVT system can produce more electrical energy than the equivalent photovoltaic system by increasing the efficiency of the solar cells and it can cover a part of the hot water demand. Past research has indicated that the liquid BiPVT system in the traditional solar domestic hot water (SDHW) configuration is not the right option because of the higher cost associated with BiPVT collectors (Matuska 2014) and (Dean et al. 2015). We consider the BiPVT collectors in nontraditional configurations to find if such systems perform better than the system in the traditional configuration.

BIPVT WITH HEAT PUMPS

A BiPVT system is heavily dependent on auxiliary heating and can only cover a part of the domstic hot water (DHW) demand. By combining BiPVT collectors with heat pumps in a single solar assisted heat pump system (SAHP), reliance on the auxiliary heat supply can be minimised. Depending on the configuration of SAHP, the COP of the SAHP can be significantly higher than the COP of a standalone heat pump system. From the solar collector's point of view, use of a heat pump lowers the entering fluid temperature to the collector and enables it to collect more heat even during periods with low solar radiation. Since BiPVT collectors, produce electricity on their own, SAHP systems can be operated either completely or partly by their own energy. SAHP is a familiar concept that is already in use for various applications including space heating and DHW production. This paper investigates if SAHP can achieve its goal of minimising the reliance on auxiliary energy, improving the COP of the heat pump and the collector efficiency all at the same time cost effectively.

CLASSIFICATION OF SAHP SYSTEMS

SAHP systems are characterised best by how the solar thermal and heat pump components interact. Freeman et al. (Freeman, Mitchell, and Audit 1979) classified SAHP as either parallel, series or dual based on the heat source interaction with the evaporator.
In a parallel combination, the heat pump works as the auxiliary energy source. Solar energy is used to meet as much of the heating requirement as possible. The heat pump does not use solar energy directly, but it is used to boost the temperature of the solar heated fluid. This system does not directly contribute to increasing the thermal efficiency of the solar collectors. The combined system also needs an additional heat source such as ground source, or wastewater. We do not include them in this study.
In a series combination, solar energy is supplied directly to the evaporator of the heat pump. A high evaporator temperature contributes to increasing the COP of the heat pump. In a slightly modified configuration, a part of the solar energy is bypassed from the heat pump when the temperature is high enough to deliver the heat directly to the load. In theory, the series system can raise both the heat pump COP and the collector efficiency. Series systems are sometimes further classified into direct series

SAHP and indirect SAHP systems. In a direct system, solar collectors work as an evaporator to the heat pump (Kuang and Wang 2006) and (Chaturvedi and Shen 1984). In an indirect SHAP system, solar collectors are rather combined with a complete heat pump unit with its own evaporator as an integrated system. Many variations of indirect SAHP exist, and some of them are investigated for this paper.

In a dual system, the heat pump evaporator receives energy from both the solar source and alternative sources like atmosphere, ground source, wastewater, etc. This system combines advantages of both the series and the parallel system and would appear to be most effective as concluded by some studies (Kaygusuz and Ayhan 1999). Nonetheless, other studies have shown this not to be true all the time (Freeman, Mitchell, and Audit 1979).

Although a lot of studies on the SAHP system and some excellent review studies (Buker and Riffat 2016), (Ozgener and Hepbasli 2007), (Hepbasli and Kalinci 2009), and (Chu and Cruickshank 2014) are available in the literature, very few were conducted with BiPVT and a water-water heat pump, and almost none for DHW production for a large-scale application like the one investigated here. Given the fact that unglazed-facade mounted PVT produces the thermal energy of the lowest grade (temperature), SAHP with this kind of collector would make more sense. Water-to-water heat pumps are selected for this study as they can be designed to operate in the wider temperature range needed for DHW production. To make the comparison between different configurations, we first define a reference system for BiPVT operating in the conventional configuration.

Simulations and Methodology

This paper uses a novel BiPVT liquid collector developed for the READY project by the Danish company RAcell Shaphire. A new TRNSYS Type "Type 230" described by (Gautam and Andresen 2017) is used to model the BiPVT collectors. The BiPVT system consists of the collectors, thermal components like heat exchangers, a storage tank and the grid-connected electrical part.

REFERENCE CONFIGURATION

The thermal part of the reference simulation model is partly based on the recommended Danish system described by IEA SHC Task 14 Advanced Active solar DHW systems (Duff 1996) for a single-family solar thermal system. The simulated system is facade mounted on the south-facing wall and uses BiPVT instead of thermal collectors. Hot solar-fluid (glycol) enters the storage tank at the top and cold fluid returns from the bottom. The storage tank has an auxiliary electric heating element with enough power to meet the peak demand during periods with low solar radiation. A constant flow pump circulates the solar-fluid. The pump has a differential temperature controller that starts and stops the circulation based on temperature levels in the storage tank. Domestic hot water (DHW) demand of 6400 l/day is heated from 10 °C to at least 55 °C. The temperature at the top of the tank is maintained at 55 °C to prevent the growth of Legionella pneumophila bacteria. A tempering valve limits DHW distribution temperature to 45 °C. The DHW demand is modelled by using the profile developed within the scope of IEA, Task 26, " Solar combisystems" (Jordan and Vajen 2001). The total heat required for DHW heating is around 95 MWh per year. Pipings, heat exchangers and pumps are not modelled to keep systems simple. These simple systems allow us to perform multiple parametric simulations around the most important components.

The electrical part of the BiPVT system is modelled as a grid connected system with a 96% efficient inverter. A daily electrical demand of the multi-family apartment is is generated with the tool developed for generating electrical demand profiles at the University of Strathclyde. A simplified schematic of the simulated BiPVT reference system is shown in **Figure 1**. The same reference case was also used earlier by (Gautam and Andresen 2017).

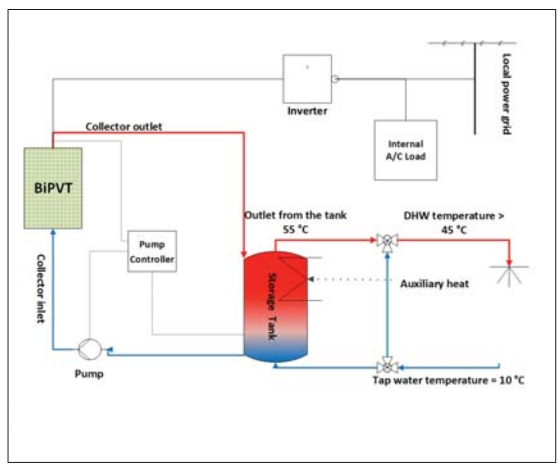

Figure 1: Schematic of the reference BiPVT system (Gautam and Andresen 2017)

The RAcell PVT has a design, that ensures good thermal contact with the fluid all the time. So high flow rates are not as critical as for the traditional designs. In fact, maintaining lower flow rates is desirable because it improves system cost effectiveness by reducing the size of pipes and pumps (Duff 1996). This analysis limits mass flow rate to the range of low flow rate.

We use GenOpt, a free to use generic optimisation software from Lawrence Berkeley National Laboratory, for automatic optimisation using the Hooke-Jeeves search technique (Hooke and Jeeves 1961). Unfortunately, global convergence is not always guaranteed, so parametric variation around relevant variables is performed to validate the results from GenOpt. The optimisation algorithm minimises the cost function (CF) as defined in (1).

$$CF = C_{tot} - LifeM_{sav} \quad (1)$$
$$C_{tot} = C_{collT}A_{coll} + C_{tank}V_{tank} \quad (2)$$
$$C_{collT} = C_{coll} + BOP_{ter} + BOP_{ele} + C_{extra} \quad (3)$$
$$M_{sav} = Life(P_{heat}Qu_{sys} + P_{grid}E_{sys}) \quad (4)$$

Table 1 shows the definitions, values and the range of different parameters used for the optimisation study. The limits for these parameters are set based on a recommendation by (Gautam and Andresen 2017). Similar optimisation is done on all other configurations that will be discussed further. The optimised values for all the systems are tabulated in **Table 1**.

SINGLE TANK CONFIGURATION

The Single tank configuration studied for this paper is similar to the one proposed by (Freeman, Mitchell, and Audit 1979), refer to **Figure 2**. The system consists of BiPVT collectors with glycol as the solar fluid, a heat pump and a storage tank. The heat pump transfers heat between glycol and water in the storage tank, utilising the higher source temperature of the solar loop to achieve better efficiency.

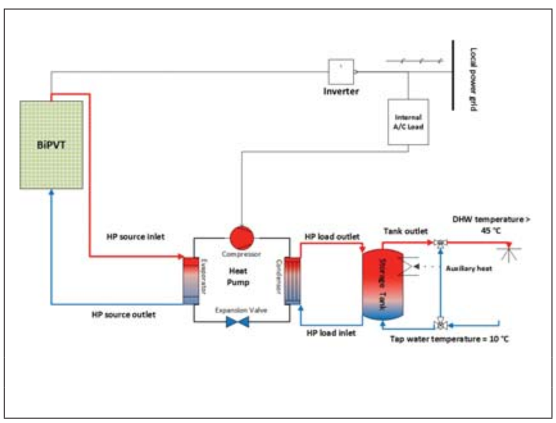

Figure 2: A simple schematic of the Single tank configuration.

The heat pump and the solar pump (not shown in the schematics) operate only when the solar-fluid can gain heat from the environment. The unglazed design of the solar collector lets it collect thermal energy from the ambient even under conditions with no solar radiation. The operation stops when the entire tank reaches an average temperature of 55 °C or when solar-fluid can no longer gain additional heat.

The BiPVT collector area for all simulations with heat pump systems is fixed at 250 m^2, which is the optimum size for the base system. The total DHW demand, the DHW supply temperature and the inlet temperature of tap water are consistent with the optimised reference system.The cost function in (1) is maximised by the optimisation algorithm.

Value of the energy saved (M_{sav}) is calculated by using the price of heat and selling price of electricity in Aarhus. While calculating total system cost (C_{tot}) extra costs associated with running pumps at higher flow rates are neglected, but the cost of the storage tank is taken into account. All the parametric and optimisation simulations are performed in a time step of 0.25 hours. After finding the optimum, the final system performance is simulated with a time step of 6 minutes.

DUAL TANK CONFIGURATION

The Dual tank configuration shown in **Figure 3** is similar to a Single tank configuration but it has an additional storage tank for the solar loop. The additional tank decreases the weather dependency of the solar side. This kind of configuration is known to perform better than other SAHP systems (Sterling and Collins 2012) and (Chu 2014). Unlike a Single tank configuration, this system can be operated at all times and seasons and can achieve a larger solar fraction.

In cold countries like Denmark, a heat exchanger is needed to transfer heat from the glycol loop to water for any combinations where heat is transferred directly from the solar fluid to water. A Dual tank configuration may have a separate refrigeration loop that eliminates the need for this heat exchanger. For the BiPVT system in cold countries, where the outlet temperature from the solar collector rarely exceeds the required DHW temperature, having a separate glycol loop is advantageous. If this configuration had a conventional solar thermal collector or if it was operating in climates with higher solar radiation, a bypass between the preheating tank and the DHW storage tank would be required.

The Dual tank configuration works with two control modes. In mode 1, the heat pump operates only when solar radiation is higher than 100 W/m^2. Fluid from the bottom of the ideally stratified storage tank enters the condenser side of the heat pump at a temperature T^{in}_{HPL}, gets heated and re-enters DHW at a temperature T^{out}_{HPL}. The uppermost node of the DHW storage tank is equipped with auxiliary heating which maintains the temperature of the top node at 55 °C. Hot solar-fluid at the temperature T^{in}_{HPS} from the preheating tank enters the evaporator side of the heat pump from the top and the cooled fluid at a temperature of T^{out}_{HPS} enters from the bottom.

In mode 2, the heat pump operates continuously until the top two nodes of the stratified DHW storage tank reach a

Table 1: Definitions and cost breakdown of the BiPVT system

Definition	Symbol	Value (unit)	Note	Reference
Cost of the collector including pipings	C_{coll}	220 €/m^2	A	(Energistyrelsen)
Balance of plant cost-electrical system	BOP_{ele}	83.3 €/m^2	B	(Energistyrelsen)
Balance of plant cost-thermal system	BOP_{ter}	40 €/m^2	C	
Additional cost	C_{extra}	50 €/m^2	E	
Cost of the storage tank	C_{tank}	1000 €/m^3	D	(Origen)
Collector area	A_{coll}	(200-300) m^2		
Volume of the storage tank	V_{tank}	(6-12) m^2		
Total system cost	C_{tot}	€		
Price of heat	P_{heat}	0.0857 €/kWh		(Fjernvarm)
Buying price of electricity	P_{ele}	0.268 €/kWh	F	
Selling price of electricity	P_{grid}	0.125 €/kWh		(Energistyrelsen)
Useful heat transferred to DHW	Qu_{sys}	kWh		
Electricity produced by the system	E_{sys}	kWh		
Estimated life of the system	$Life$	20 years		
Value of the energy saved	M_{sav}	€		

A: Lowest price offered if BiPVT is bought on a large scale, based on personal correspondence with RAcell.

*B: 0.49 (€/*Wp*), includes installation cost.*

C: Cost of pump and fitting excluding storage.

D: Based on market prices for a storage tank with a volume of at least 6 m^3.

E: Includes lifetime O&M costs.

F: Average electricity price. The price depends on the spot price of electricity and different taxes based on the use.

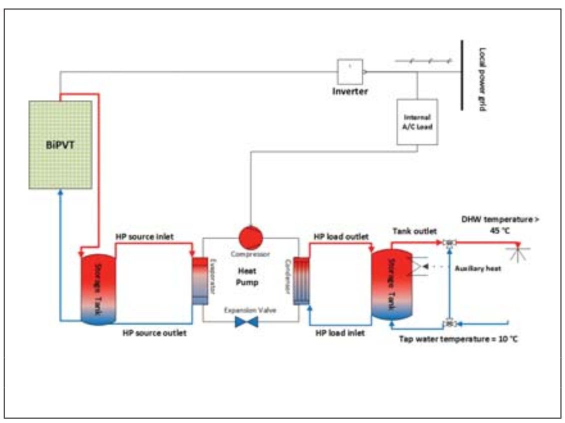

Figure 3: A simple schematic of the Dual tank configuration.

temperature of 55 °C. The solar pump is controlled independently of the heat pump operation, and it turns on if the outlet temperature of the solar collector can be 5 °C warmer than the temperature at the bottom of the preheat tank. The heat pump turns off if the entire tank reaches an average temperature of 55 °C in both modes.

Electricity prices, when bought from the grid, are as high as 3.5 times the heat price (Gautam and Andresen 2017). Operating the heat pump with the electricity bought from the grid is expensive since the selling price of generated electricity is almost half the buying price. Thus, maximum operation is desired during the time when BiPVT produces its own energy. Both modes of operation prioritise this, but mode 1 strictly limits the heat pump operation to the period in which it can operate with its own electricity.

FILL TANK CONFIGURATION

In this combination, preheated water from the solar collectors is reheated to the desired temperature by the heat pump. The evaporator side of the heat pump also uses solar energy as a source. This configuration is understudied in the literature, but this system can be an excellent choice for a BiPVT system that is not capable of directly supplying high-temperature water. (Bai et al. 2012) mentioned a variation of this setup in their study of sports centre water heating with PVT collectors. The Fill tank configuration being investigated is a modified version of that system.

The Fill tank configuration shown in **Figure 4** consists of BiPVT for solar preheating. A differential controller, exactly like in the traditional SDH systems, controls the solar side of the system. Hot solar-fluid enters the preheat tank seeking the closest temperature node and exits to the collector from the bottom. A solar pump with a constant flow rate turns on when BiPVT can collect useful energy, i.e., when the outlet temperature from the collector is at least some degrees higher than the temperature at the bottom of the preheat tank.

Preheated water exits the top of the preheat tank for reheating with the heat pump because in our case the temperature at the top of preheat tank does not exceed 55 °C. If this system was operated in warmer climates or had nor-

Table 2: *Optimum values for different configurations*

		Reference	Single Tank	Dual Tank		Fill Tank	
				Mode 1	*Mode 2*	*Mode 1*	*Mode 2*
Storage tank volume (m^3)	*Pre-heat*	x	x	2.5	4	5.5	5.5
	DHW	8	5	5.5	5.5	5.5	5.5
Mass flow rate (kg/h)	*Solar side*	3375	3900 glycol	2500 glycol	2500 glycol	2750 glycol	2750 glycol
	HP Source	x	x	1060 glycol	1060 glycol	1075 glycol	1075 glycol
	HP load	x	2000 water	1045 water	1045 water	1050 water	1050 water

Optimum collector area for the reference configuration is 250 m^2. *The same collector area is used for all other configurations.*

mal solar thermal collectors, a bypass valve would typically be required. The water-to-water heat pump uses moderately warm temperature, T^{in}_{HPS}, from the middle part of the tank as a source. Replacement water at 10 °C enters the preheat tank at the bottom and mixes with the cold return water at $Tout_{HP}$ from the source side of the heat pump. The heat pump boosts the preheated water and cools down the moderately hot water in the tank, lowering the inlet temperature (T^{in}_{coll}) to the BiPVT, which is expected to increase the thermal efficiency of the process.

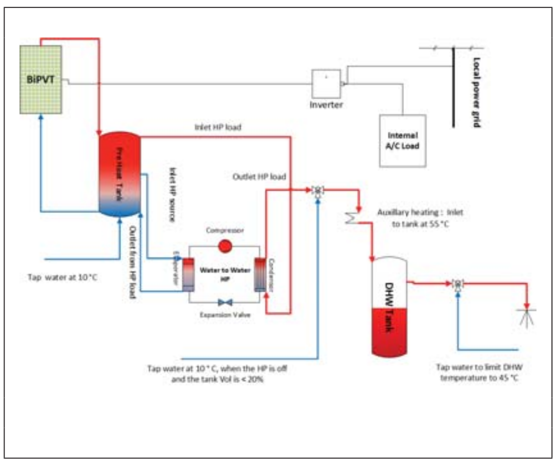

Figure 4: Schematic of the Fill tank configuration.

The supply side has a fill tank to store reheated hot water from the heat pump. In optimum conditions, the fill tank, is desired to be filled with reheated water during the day when the heat pump can operate solely with the electricity produced by BiPVT. The DHW demand gradually empties the fill tank, and the cycle is repeated. The heat pump is dimensioned to raise the temperature of preheated water by about 20 °C, and fill the DHW tank with about 5 hours of operation. During the period when the reheated water from the heat pump is not at the required DHW storage temperature, it is heated by an auxiliary heat source to 55 °C before entering the fill tank.

The heat pump operates in two modes. In mode 1, like the Dual tank configuration, the heat pump turns on only when solar radiation is enough to power it directly. In this mode, when the heat pump is off and the volume of the DHW tank is less than 20% of its capacity, a fill pump supplies cold water at 10 °C. This water is heated entirely by an auxiliary energy source. The fill pump turns off immediately when the tank is 20% full. This operation is somewhat similar to instantaneous water heating but with a small storage. In mode 2, there is no fill pump. The Heat pump functions like the fill pump during the period with no solar radiation. The heat pump turns off if the DHW tank is full in both modes. The DHW tank, in this configuration is just a temporary storage unit, and unlike other systems, it is not equipped with internal heaters. Water with a temperature of less than 55 °C never enters the fill tank. The fill pump controller ensures that the tank volume is always less than full and more than 10% of the total volume.

MODELLING OF HEAT PUMP

Although not thermodynamically impossible, commercially available water-to-water heat pumps do not allow source side inlet temperature to exceed 30 °C. The Trane heat pump only allows it to be maximum 26.7 °C. For the Single and the Dual tank model, the inlet source temperature exceeds the given maximum for the heat pump used in the simulations. The few authors who have done similar studies with water source heat pumps for solar applications have either used analytical models for water-to-water heat pumps (Bridgeman 2010), or manipulated the manufacturer's data with some experiments (Chu 2014). We have linearly extrapolated the heat pump data beyond the given operational temperature range with a MATLAB routine.

RESULTS

Figure 5 and **Figure 6** show the detailed monthly energy production per unit area of the optimised reference system with a collector area of 250 m^2. Because of the vertical orientation, the total incident solar radiation is almost uniform for the months between March and September. Similar is the energy production. The difference between the thermal energy yield by collectors and the energy delivered to DHW represents the thermal losses of the system. The total thermal yield by collectors is 140.3 kWh/m^2, which corresponds to an overall thermal efficiency of 15.73%.

The system provides 33,870 kWh heat to DHW, which meets 35.5% of the overall demand of 9.52 MWh. One m^2 of BiPVT produces 109.3 kWh electricity. After inverter losses of 4%, 60 kWh is supplied to the in-house load, and the rest is sold to the grid. The system produces 31.6% of the total electricity consumption of 9 MWh, but only supplements 16.5% of the total electrical demand directly.

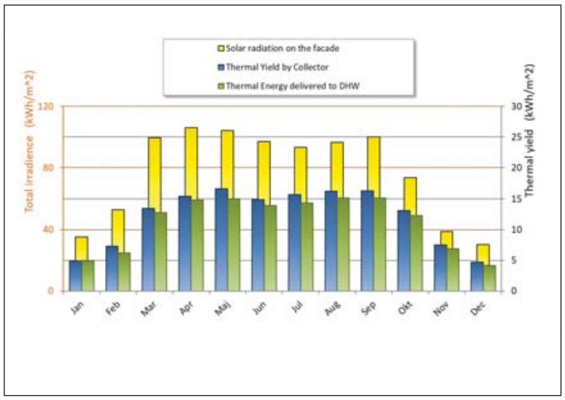

Figure 5: Thermal energy yield (per m^2*) of the optimised reference BiPVT configuration.*

The expected cost of installing this system is approximately €97,500. If we consider the system to sell all its electrical production, it will generate approximately €6,400 yearly. This corresponds to a simple payback period, without considering interest rates, of 15.3 years, which is not a good business case. If we calculate internal electric demand fulfilled by the system with the buying price of electricity, the payback time decreases to 11.5 years (Gautam and Andresen 2017).

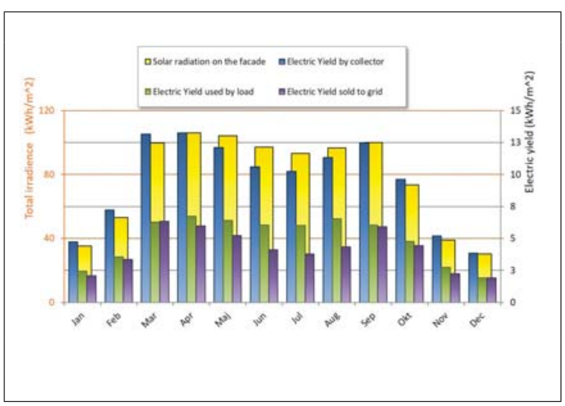

Figure 6: Electric energy yield (per m^2*) of the optimised reference BiPVT configuration.*

PERFORMANCE COMPARISONS

Thermal efficiency (η_{term}) and electrical efficiency (η_{ele}) are defined as a ratio of energy produced by BiPVT to available solar radiation (S) calculated as an annual average. These efficiencies are additive. The total amount of heat collected by the collector (Qu_{coll}) and the total electricity produced by the collector (E_{coll}) are raw energy produced in a year and do not include system losses. These values are used to calculate the thermal and the electrical efficiency. Useful heat gain from the system (Qu_{sys}) is the heat that is delivered to DHW. The useful electricity (E_{sys}) is the electricity that is available for use after the inverter losses of 4%. Solar fraction (SF) is the fraction of DHW demand supplied by the system without an auxiliary energy source.

$$\eta_{term} = \frac{Qu_{coll}}{S} x100\% \qquad \eta_{ele} = \frac{E_{coll}}{S} x100 \tag{5}$$

$$SF = 1 - \frac{Qu_{Aux}}{Q_{DHW}} \qquad COP = \frac{Qu_{HP}}{E_{HP}} \tag{6}$$

For configurations with heat pumps, the heat delivered by the heat pump (Qu_{HP}) is not considered as the auxiliary energy (Qu_{Aux}). The total DHW demand (Q_{DHW}) is the amount of heat added to DHW. The average COP of the heat pump is a ratio of Qu_{HP} and the total heat pump energy use (E_{HP}). Q_{sav} and M_{sav}, are total energy saved and value of the energy saved, calculated in kWh and € , respectively. M_{sav} is calculated with the heat price (P_{heat}), the buying price of electricity (P_{ele}) and the selling price of electricity (P_{grid}) in Aarhus.

$$Q_{sav} = Qu_{sys} + E_{sys} - E_{HP} \tag{7}$$

$$M_{sav} = P_{heat} Qu_{sys} + P_{grid}(E_{sys} - E_1) - P_{ele} HP_{grid} \tag{8}$$

$$E_1 = E_{HP} - HP_{grid} \tag{9}$$

The value of produced electricity is assumed equal to the selling price to the grid. For operations in mode 2, electricity required by the heatpump during the period with solar radiation less than 100 W/m^2 (when BiPVT cannot produce its own electricity) is considered to worth (P_{ele}).

For all the heat pump operations, we neglect the internal electric demand and assume that all electricity is either used by the heat pumps or sold to the grid. A payback time is a simple ratio of total system cost (C_{tot}) and M_{sav}. C_{tot} for the PVT system and the storage system is estimated with the values listed in the **Table 3**. We assume that the 21 KW heat pump used in the simulation, costs €8,000. The performance measures of all configurations are tabulated in **Table 3**.

The **Table 3** shows that the Fill tank configuration operating in mode 2 is the best of all configurations if we consider the M_{sav} and payback time as the most important

Table 3: Comparison of key outputs between different Solar Assisted Heat Pump (SAHP) configurations. Best values in each row are shown in bold.

Parameters	Reference	Single Tank	Dual Tank		Fill Tank	
			Mode 1	Mode 2	Mode 1	Mode 2
η_{term} (yearly average)	16%	19%	21%	**31%**	21%	23%
η_{ele} (yearly average)	11.80%	11.77%	11.88%	**11.96%**	11.94%	11.95%
Qu_{sys} (kWh/year)	33979	54493	55765	**92162**	52219	56454
E_{sys} (kWh/year)	27339	27251	27524	**27701**	27644	27686
Qu_{HP} (kWh/year)	-	57498	58503	97060	**32841**	39644
E_{HP} (kWh/year)	-	13206	10725	25918	**6225**	7057
Qu_{Aux} (kWh/year)	61189	40672	39404	**2997**	42944	38708
COP (yearly average)	-	4.35	5.45	3.74	5.28	**5.62**
SF (yearly average)	0.36	0.57	0.59	**0.97**	0.55	0.59
Q_{sav} (kWh/year)	61318	68539	72564	**93945**	73638	77083
HP_{grid} (kWh/year)	-	3145	-	13629	-	983
$\$_{sav}$ (€/year)	6380	6032	6936	6254	7211	**7338**
System cost (€/year)	97325	102325	105325	106825	108325	108325
Payback (years)	15.3	17.0	15.2	17.1	15.0	**14.8**

parameters. The Fill tank configuration in mode 2 has a higher COP than in mode 1 because in the configuration where the heat pump operates only when there is solar radiation, a large part of the collected hot water is cooled down naturally at the end of the day. Operation like that of mode 2 utilises the heat collected during the day, minimise the temperature of the preheat tank and improve the overall efficiency of the solar collector. The overall COP of the Fill tank configuration is high because the heat pump uses a relatively warm source and only has to heat preheated water.

The Dual tank configuration operating in mode 2 is the best energy-wise. This configuration produces the highest amount of energy, covers almost all the load requirements, and maximises the thermal and the electrical efficiency. This system would be an excellent choice as a stand-alone system in areas that do not have a district heating grid. Because of the current pricing structure of electricity, it is bad choice economically. The Dual tank configuration can cover 100% of the load with the same heat pump if the control scheme was different to the one we defined. We limited the operation of the heat pump to only heat the top two nodes of the tank to 55 °C under no solar radiation conditions because it would be unwise to heat the full tank to 55 °C all the time. The COP of this system is lowest of all because it has to rely on a relatively cold preheat tank during operation with no solar radiation.

The Single tank configuration is slightly better than the reference system energy-wise but worst of all the systems in most regards. The reference system is, surprisingly, very competitive with all the complicated systems with heat pumps. In a situation like that in Aarhus, where the heat market is well regulated and functioning, the simple reference system fares quite well.

Regarding the implementation, the Fill tank configuration is probably the better one, for ease of installation and the control of growth of Legionella pneumophila bacteria. In this setup, water at a temperature less than 55 °C is never stored in the distribution loop, which prevents the growth of Legionella pneumophila, as the bacteria favour temperatures below 45 °C. In the current situation, with Aarhus moving towards low-temperature district-heating, the hot water from the heat pump of the Fill tank configuration may be stored in the district heating loop directly and replace the storage tank entirely. The idea of storing hot water during the day, when a solar thermal system produces heat for use in the night in a variable volume tank can be an interesting experiment that future installations with solar heating can follow. Not many manufacturers produce such variable volume tanks, so finding one in the market may present a challenge. The Dual tank concept has its own challenges. Commercially available water-to-water heat pumps, as mentioned in earlier chapters, do not allow source side inlet temperature to exceed 30 °C. Thus, a little more effort might be needed to order one, especially for this application.

CONCLUSION

SAHP systems improve the performance of the reference system by increasing the total energy production. However economically, only a few setups are better than the reference system, but not by a large margin. Further, the electrical production from BiPVT could offset high-value utility bills instead of powering the heat pump, so the overall economic productivity of the reference system is actually higher than our assumption that all the electricity is sold. Therefore, we conclude that the reference system (the system without the heat pump) is the best system economically for the current utility prices in Aarhus.

There is only a small difference in payback times obtained from the different configurations. The parameters like electricity to heat price ratio, buying and selling price of electricity heavily influence this number. Thus, other parameters should be considered in the places where the heat to electricity price or the buying and the selling price of electricity are different. Using the parameters listed in **Table 3**, payback time and cost related parameters can be calculated for other places with a similar climatic condition.

ACKNOWLEDGMENT

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