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Evaluation of the Combination of Hybrid Photovoltaic Solar Thermal Collectors with Air to Water Heat Pumps

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Abstract

Recently, hybrid photovoltaic solar thermal collectors (PVT) became a topic of many research projects because of the possibility to gain heat and electricity simultaneously. PVT represents the alternative to PV panels and solar thermal collectors in one device. The main goal of this study is to evaluate different possibilities to integrate PVT collectors in an air to water heat pump system and to compare the results with the combination of an air to water heat pump system together with a PV-system. Three different hydraulic systems for the heating system integrated with PVT have been simulated in this study. The possible increase of self-consumption and reduction of primary energy consumption by applying a special control to store electrical energy as heat has been investigated. The effect of this control on the performance of the PVT collectors has been determined. Full costs for the different heating systems were calculated.

Keywords: PVT, air to water heat pump, load shifting, PV, energy management, Demand Side Management.

1. Introduction

A recent research topic is the coupling of heat pumps with PV systems to reduce the primary energy consumption for heating and to increase the self-consumption of the produced PV energy. It seems obvious to use hybrid photovoltaic thermal solar collectors (PVT) in order to profit from PV energy to drive the heat pump as well as to use the produced heat to increase for example the temperature at the evaporator of the heat pump and therefore the system efficiency. To evaluate such system concepts a simulation study has been conducted. An air to water heat pump combined with PV panels has been simulated and used as a reference to evaluate the performance of the air water heat pump systems combined with PVT.

2. Simulation components

The dynamic simulation model in TRNSYS 17[1] consists of a single family house and a heating system. An air to water heat pump (AWHP) is the main heat source in this study. The heating system utilizes a stratified storage tank to supply domestic hot water, to decouple the heat pump runtimes from the building`s heat demand and to store thermal energy generated from the PVT collectors (see figures (1-3) for schemes of the systems with PVT). The AWHP system is complemented in the reference system by a PV system (the system is realized analogous figure (1), whereby PVT is replaced by PV and therefore no hydraulic connection of the modules is needed). Where in all systems the electricity produced is at first supplied to the household, then to the heating system and at last to the electrical grid. The control strategy to store energy generated by PV as heat, developed in Abdul-Zahra et al. (2014), has been implemented in the simulation. This control is denoted in the latter as load shifting. Table 1 summarizes the boundary conditions of the simulation model.

It seems obvious to replace the PV panels in the reference system with PVT collectors, to not only generate electricity but also heat, which can be used to increase the temperature at the evaporator of the heat pump or

[1] http://www.trnsys.com

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to use the heat direct to cover the space heating and hot water demand.

Table 1: Assumed boundary conditions of the reference simulation model.

	Reality / Assumed	Model in TRNSYS
Location	Würzburg, Germany	Meteonorm dataset
Building type	Residential building	Type 56
Heated living area	180 m²	Building model based on (Faßnacht, 2015)
Yearly overall heat demand	9450 kWh/a	
Total domestic hot water demand	2050 kWh/a	Profile based on IEA Task 44 (Dott et al., 2012)
Occupancy	4 persons	
Household electricity consumption	4141 kWh	Profile based on VDI 4655 (VDI 4655, 2008)
Storage tank	1000 ltr. (Consolar Solus II)	Type 340 (Drück, 2006)
Air to water heat pump	8 kW (Dimplex LA8PMS)	Type 401 (Wetter and Afjei, 1996)

A further improvement by PVT is the increased generated electricity, due to the cooling of the solar cell[1]. In general there can be distinguished covered and uncovered PVT collectors. Covered PVT is utilized with an air gap and a glass plate above the solar cell to minimize convective heat losses and therefore to reach higher collector temperatures. This set up has the disadvantage of lower PV yields, due to the optical losses caused by the glass plate and the higher module temperatures. Uncovered PVT collectors are normally PV modules equipped with a piping system and insulation on the backside. Due to the higher PV yield and the easy realization and therefore cheaper costs of uncovered PVT, these collectors are at present the state of art. Therefore in this study an uncovered PVT collector has been taken into account. The PVT collector has been simulated with the TRNSYS Type 203, which has been developed by the ISFH Hameln (Germany) in the Project Bi-SolarWP (Project BiSolar-Wärmepumpe). More information about the Type, which couples the EN 12975 (DIN EN 12975-2, 2006) thermal collector and the EN 60904 (DIN EN 60904-8, 1998) PV model, can be taken from Stegmann (2011). In this study a Solimpeks (Solimpeks Solar GmbH) Volther PVT collector has been simulated. Table 2 summarizes important parameters of the PVT model taken from the data sheets. To realize a fair comparison between the PV modules and PVT collectors, the PV system was simulated with the same Type 203 and the same area and parameters, but without connection of the hydraulic pipes and therefore no active cooling and thermal heat gains, as normal in PV modules. In all 4 systems an identical area of 23.8 m² (= 3.5 kWp PV power) has been simulated.

Table 2: Parameter of the PVT model.

Parameter	Unit	Value
Aperture area	[m²]	1.32
Conversion factor Ƞ (thermal)	[-]	0.67
Heat loss coefficient a1	[W/m²K]	11.4
Electric conversion factor	[%]	14.9
P_{max} thermal	[W]	629
P_{max} electrical	[W]	200
Temperature coefficient of the PV module	[%/K]	-0.5
MPP voltage of the PV module	[V]	36.8

[1] The electrical energy generated by PV cells depends on the cell temperature of the panels. There is an inverse relation between the cell temperature and the energy generated by the PV, where every Kelvin above the reference temperature of 25 °C cell temperature leads to a decrease in the electrical energy generated by PV (Skoplaki and Palyvos, 2009).

Open circuit voltage of the PV module	[V]	46.43
MPP current of the PV module	[A]	5.43
Short-circuit current of the PV module	[A]	5.67

3. System simulation

Three different hydraulic systems for the integration of PVT collectors into an AWHP system have been simulated in this study and were compared to each other and the reference system AWHP+PV. In all cases a total PV/PVT area of 23.8 m² was simulated. The generated electrical energy by PV/PVT is always supplied to the household demand, then to the heating system and at last to the grid. Also in all cases the basic control of the heat pump was implemented via standard hysteresis control, whereas the control for hot water recharge is defined by:

$u_{HP} = 1$ IF $T_{S1} < 52$ °C $- 5$ K AND THEN UNTIL $T_{S1} \geq 52$ °C (eq.1)

and for space heating by

$u_{HP} = 1$ IF $T_{S2} < T_{set}$ AND THEN UNTIL $T_{S2} \geq T_{set} + 3$ K. (eq.2)

Where T_{S1} and T_{S2} are measured temperatures in the storage tank (see figure (1)), u the control signal of the heat pump (1 is ON, 0 is OFF) and T_{set} is the set temperature of the water supply to the building calculated via the heating curve, where the heating curve is a nonlinear function of the ambient temperature. The condenser pump (pump 1 in figures (1-3)) is operated always simultaneous to the heat pump.

To store electrical energy generated by PV/PVT as heat (load shifting) in all cases the following control has been applied:

$u_{HP} = 1$ IF $PV_{surplus} > PV_b$ AND $T_{S2} < T_{max}$ (eq.3)

Where T_{max} is the maximum allowed temperature in the storage tank while load shifting (in this study T_{max} was set equal to 62 °C) and PV_b a boundary $PV_{surplus}$ power at which the load shifting starts (in this study for January, November and December PV_b was set equal to 500 W, for February, March and October PV_b to 750 W and from April to September to 1250 W). For more information about this control see Abdul-Zahra et al. (2014).

3.1. System1 - PVT thermal energy supply to a stratified storage tank:

In the first system, as shown in figure (1), the thermal energy generated by PVT is supplied directly to a storage tank along with the heat generated by the heat pump. A 1 m³ stratified storage tank has been used (see table 1).

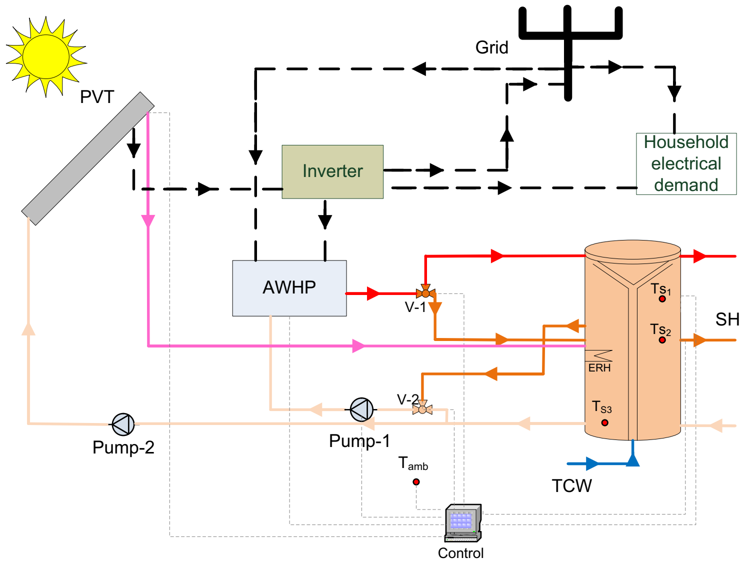

Fig. 1: System 1: thermal energy generated by PVT is supplied to a stratified storage tank.

The following control strategy for the PVT system has been implemented:

The solar pump (pump 2) will run to collect heat from the PVT modules when

$T_{PVT,out} > T_{S3} + 5\,K$ AND THEN UNTIL $T_{PVT,out} < T_{S3} + 1\,K$ (eq.4)

Where $T_{PVT,out}$ is the outlet brine temperature of the PVT collectors and T_{S3} the temperature in the bottom of the storage tank.

3.2. System 2 - PVT thermal energy supply either to the stratified storage tank or the heat pump:

In the second system the heat generated by PVT is either supplied to the evaporator of the heat pump or to the stratified storage tank, as shown in figure (2). The goal hereby is to increase the evaporating temperature of the heat pump and to cover a part of the heat demand directly with the generated heat of the PVT modules. A brine/air cross flow heat exchanger to preheat the inlet air flow in the evaporator of the heat pump has been used. Type 91 in TRNSYS 17 has been used for the simulation of the heat exchanger[1].

The heat from the PVT collector is supplied to the brine/air heat exchanger if

$T_{PVT,out} > T_{amb} + 5\,K$ *and* $T_{PVT\_out} < 30\,°C$ *and HP is ON*. (eq.5)

and then until

$T_{PVT,out} < T_{amb} + 1\,K$ *or* $T_{PVT\_out} > 30\,°C$ *or HP is OFF*. (eq.6)

If the *HP* is *OFF* or $T_{PVT\_out} > 30\,°C$, the thermal energy is supplied to the stratified storage tank if

$T_{PVT,out} > T_{S3} + 5\,K$ AND THEN UNTIL $T_{PVT,out} < T_{S3} + 1\,K$. (eq.7)

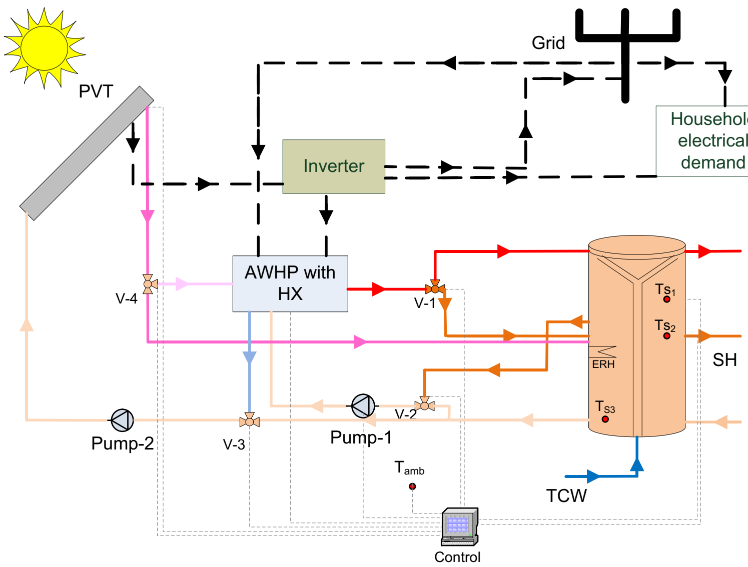

Fig. 2: System 2: the heat generated by PVT is supplied either to the evaporator of the heat pump or to the stratified storage tank.

3.3. System 3 - PVT thermal energy supply to a secondary storage tank:

The simulations of systems 1 and 2 has shown that the load shifting (run the heat pump, when PV surplus is available) leads to a dramatic reduction of the efficiency of the solar thermal collectors due to an increase of the operation temperature in the tank by the load shifting process. Therefore, in the third system, as shown in figure (3), the heat generation by PVT is supplied to a secondary small storage tank (300 L) which is used to preheat the domestic hot water before supplying it to the primary stratified storage tank (1000 L), and to supply energy to the stratified storage tank, if the temperature in the top of the secondary storage tank is higher than the temperature in the bottom of the primary storage tank. The goal hereby was to decrease the operating temperatures of the PVT collectors and thus to increase the efficiency of the solar thermal collector. For this system two pumps (pump 2 and 3 in figure (3); pump 1 starts always with the heat pump) have to be triggered:

Pump 3 runs when

[1] The (constant) heat exchanger effectiveness of the model has been chosen to 0.9.

$T_{PVT,out} > T_{PVT,stb} + 5\,K$ AND THEN UNTIL $T_{PVT,out} < T_{PVT,stb} + 1\,K$. (eq.8)

Pump 2 runs when:

$T_{PVT,st} > T_{ST,b} + 5\,K$ AND THEN UNTIL $T_{PVT,st} < T_{ST,b} + 1\,K$. (eq.9)

Where $T_{PVT,st}$ is the temperature in the top of the secondary storage tank, T_{STb} the temperature in the bottom of the primary storage tank and $T_{PVT,stb}$ the temperature in the bottom of the secondary storage tank (see figure (3)).

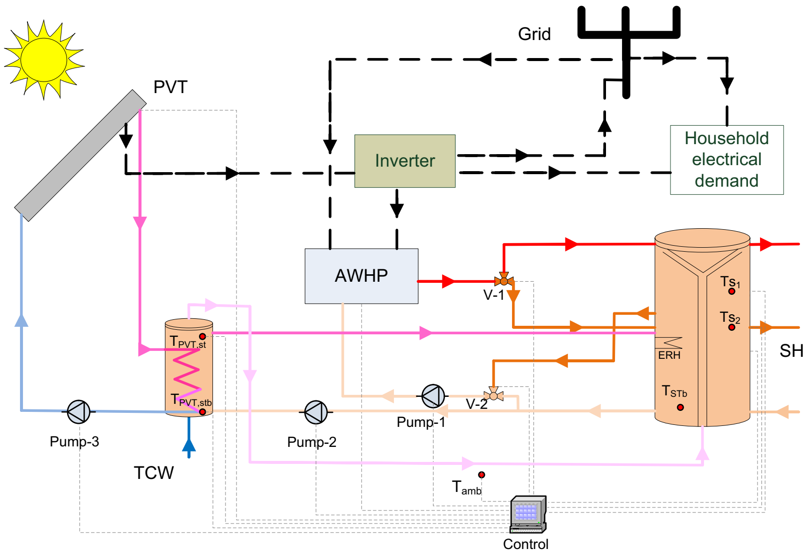

Fig. 3: Third system: heat generated by PVT is supplied to a secondary small storage tank.

4. Full cost calculation

In order to compare the different heating systems full cost calculations for all systems have been performed. The calculations were done based on the annuity method in VDI 2067 (VDI 2067, 2000). Tables (3, 4) summarize the price assumptions of the components and energy.

Table 3: Assumed component prices.

Product	[Euro]
Storage tank (1 m³, all systems)	3000
Secondary storage tank (0.3 m³, system 3)	600
Heat exchanger (system 2)	300
PV total[1] (€/kWp; ref. system)	1750
PVT (€/per collector; system 1-3)	400
PVT solar small parts[2]	2464
Total investment costs[3] system 1	35844
Total investment costs system 2	36201
Total investment costs system 3	36558
Total investment costs reference system	32305

Table 4: Energy prices, price increase rates and interest rates.

Energy Source	Value
Energy price increase per year	5 %

[1] Turnkey ready: Incl. inverter, assembly-kits, installation, according to (Harry 2014).

[2] The small parts includes (solar station, connecting kit, 3-way changeover valve, solar control valve, expansion vessel, solar heat transfer fluid, automatic air ventilation, inverter and installation).

[3] The total investment costs include in all systems additionally the following parts: heat source completely (heat pump, control, etc.) = 8700 €, heat distribution= 5500 €, heating system installation= 3000 €, connection from the heat pump to the storage tank = 1800 €).

Maintenance cost price increase per year	2 %
Inflation rate	2 %
Imputed interest	3 %
VAT	19 %
Lifetime (year)	20
Electricity (€cent/kWh)	25.7
Electricity Feed-in (€cent/kWh), constant	15

5. Performance indicators

In order to evaluate the heating systems, different figures of merit were calculated based on the simulation results.

5.1. Primary energy consumption and CO_2-emission

Beside the full cost calculation, primary energy consumption and CO_2-emission were the metrics to compare the different systems. The primary energy factor of electricity was chosen to 2.6 and the CO_2 factor to 0.617 [kg/kWh] according to EnEV 2009 and prEN 15203 [(EnEV 2009 (2009) and prEN 15203/15315 (2006)). Electrical energy fed into the electrical grid has not been considered in these calculations. It is assumed, that electrical energy fed into the grid is indirectly already reflected by falling primary energy factors for electricity. The balance boundary of the calculations is the whole building and not only the heating systems. Therefore, the calculated primary energy demands and CO_2-emission are for the electrical household and the heating demand.

5.2. Autonomy and Self-Consumption

To evaluate the effect of the load shifting and the hydraulic system, the autonomy has been calculated. The autonomy is the ratio of the total locally used energy from PV panels to the total electrical energy demand in the building (both household demand and heating):

$$Autonomy = \frac{\sum PV_{Local}}{\sum el.Total} \qquad \text{(eq.10)}$$

Where *el. Total* is the total (electrical) energy consumption (for heating and the household) in the building. The self-consumption is the ratio of the total locally used energy from the PV system (household demand and heating system) to the total energy generated from the PV system per year.

$$Self - Consumption = \frac{\sum PV_{Local}}{\sum PV} \qquad \text{(eq.11)}$$

Where PV_{local} is the energy consumption from local PV panels.

5.3. Seasonal performance factor

The seasonal performance factors (SPF) of the systems were calculated according to (Malenkovic et al., 2012):

$$SPF = \frac{\int (Q_{SH}+Q_{DHW})\mathrm{dt}}{\int (E_{hp}+E_{ERH}+pump_2+pump_3+pump_1+E_{Control})\mathrm{dt}} \qquad \text{(eq.12)}$$

Where

SPF: Seasonal Performance Factor

E_{hp}: Energy consumption by the heat pump

E_{ERH}: Electrical resistance heater energy consumption

Q_{SH}: Space heating demand

Q_{DHW}: Domestic hot water (DHW) heating demand

$E_{Control}$: Energy consumption by the control system and valves.

6. Results

6.1. Primary energy consumption and CO_2-emission:

In all systems the application of the control for load shifting has a significant effect on the primary energy consumption, due to the reduced electrical energy demand from the grid (see figure (4)).[1] The usage of PVT collectors instead of PV panels can reduce the primary energy consumption (and CO_2-emission) up to 4.5 % without load shifting. However, this saving is reduced to 2.2 % when the control of load shifting is applied, due to the increased operating temperatures of the storage tank, which led to reduced PVT thermal efficiency. In **system 1** for example without shifting 576 kWh thermal energy is delivered to the storage tank, whereas with load shifting just 42 kWh can be delivered anymore. **System 3** presents as the most efficient hydraulic system for the integration of PVT. This is due to the relative low operating temperatures of the PVT collectors, which can be achieved with the concept, which result in higher thermal and electrical efficiency. With system 3, 1166 kWh thermal energy is supplied from the PVT collectors to the storage tanks without load shifting and 990 kWh with load shifting. The effect of preheating air of the evaporator with heat from the PVT collectors in **system 2** was surprisingly low. Without load shifting the difference in primary energy consumption of system 1 and 2 is very small. The thermal energy supplied directly to the storage tank stays here nearly the same (571 kWh with system 2), additionally 429 kWh can be delivered to the heat pump, but what only results in a 1.5 % increase of the SPF of the heat pump. Interestingly the achievable effect is bigger, when the control for load shifting is applied. Admittedly now the direct delivered energy to the storage tank decreases just as in system 1 to nearly zero (42 kWh), but 1842 kWh can then be delivered to the heat pump. This is due to the fact that with load shifting the heat pump runs more often at the daytime, whereby the thermal energy supply and the thermal energy demand of the evaporator of the heat pump fit better together.

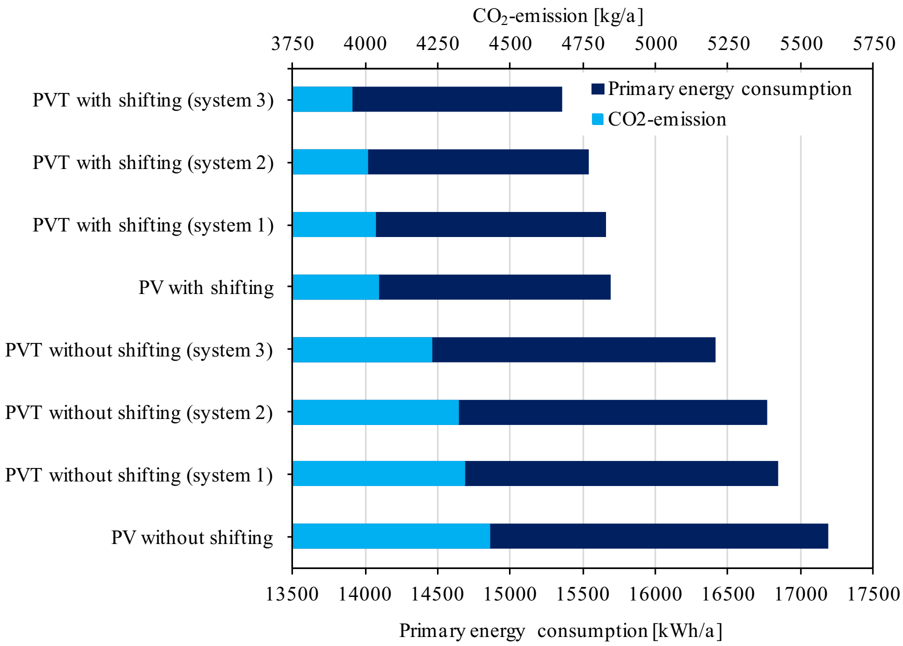

Fig. 4: Primary energy consumption and CO_2-emission of the different evaluated cases.

6.2. Self-consumption and Autonomy:

Figure (5) depicts the effect of load shifting on the self-consumption and autonomy of the different systems. In all 4 cases a clear benefit of the storage of locally generated PV energy as heat can be observed. The individual differences between the systems are very small, this is due to the fact that the electrical generation of all 4 systems is nearly the same (the best PVT system 3 generated just 1 % more than the reference system with PV) and also the overall electrical demand of the buildings don't differ in big magnitudes. Therefore

[1] Note: If fed electrical energy into the grid would be taken into account in the primary energy calculation, it would normally yield lower primary energy consumptions if all electrical energy is fed into the grid, due to the storage losses. But the boundary condition in this study was set to the building and the goal was to reach maximum local consumption of renewable energy.

also the autonomy and self-consumption results in comparable numbers.

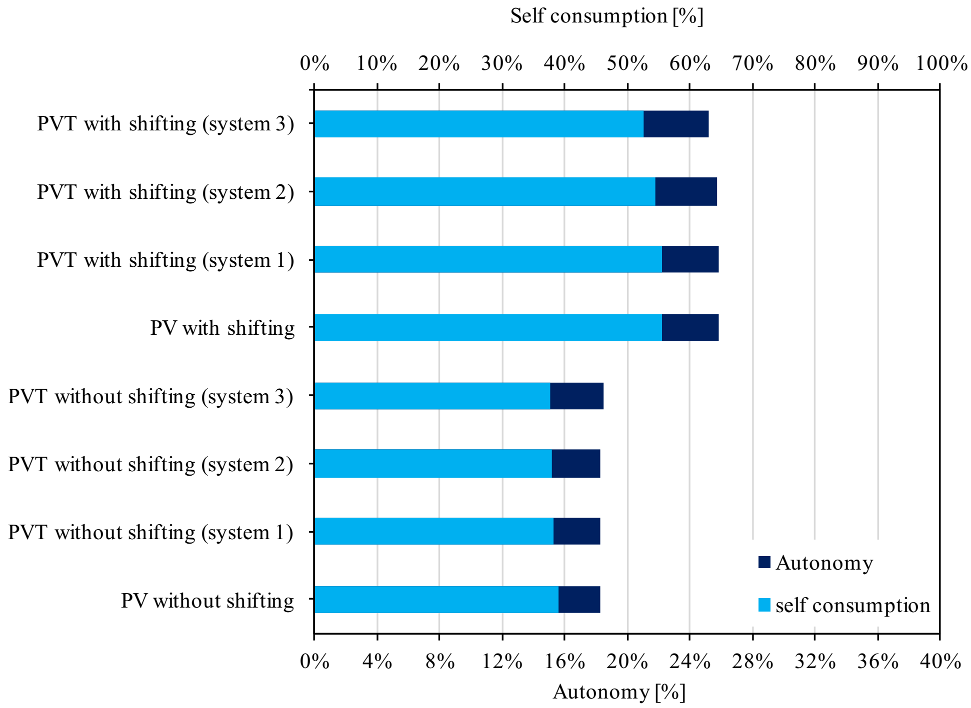

Fig. 5: Self-consumption and autonomy of different heating systems.

6.3. Seasonal performance factor:

The results of the simulation show that the SPF of the heating systems with PVT is higher than the SPF of the heating system with PV because of the additional heat generated by the PVT collectors (see figure (6)). System 3 results in the highest SPF, due to the lower storage tank temperatures and therefore higher thermal efficiency of the PVT collectors.

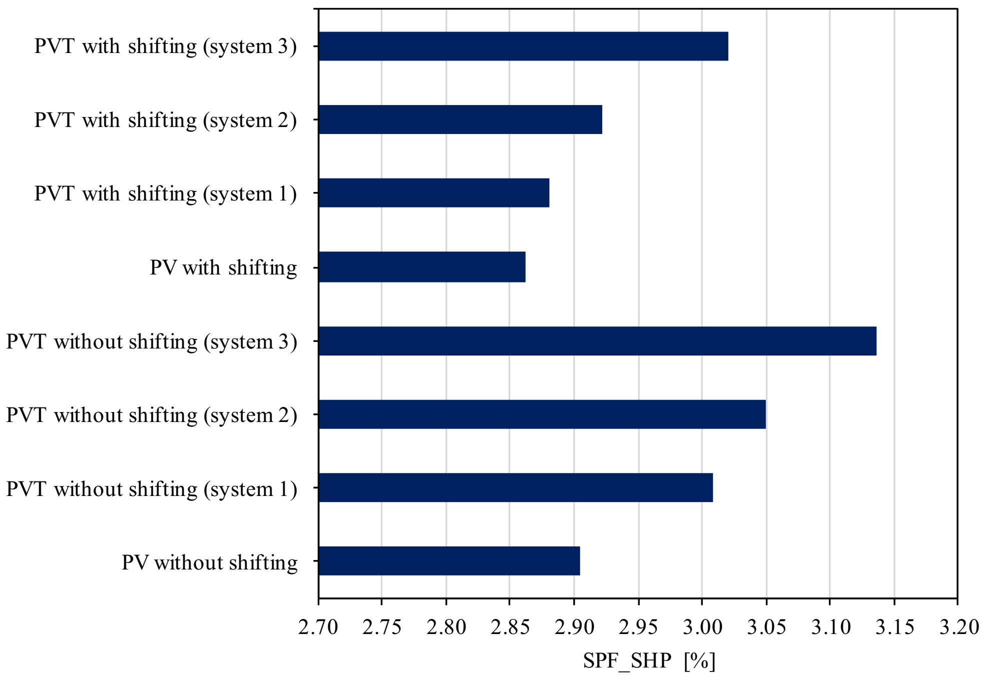

Fig. 6: SPF of the four systems proposed in this study.

The application of load shifting had a relative small effect on the SPF of the AWHP+PV system. Admittedly the load shifting results in higher temperatures in the storage tank and condenser temperatures of the heat pump, however in a lower runtime of the heat pump for hot water, due to the pre heating of the hot water in the middle and lower parts of the storage tank. In the systems 1, 2 and 3 with PVT, the load shifting clearly leads to lower SPF values. This is caused by the reduced efficiency of the thermal collectors with the increase of the operation temperature of the storage tank. When load shifting is applied, the SPF of system 1 with PVT and the reference system (AWHP+PV) is nearly the same. This is due the already mentioned effect, that when load shifting is applied not much heat of the PVT can be supplied directly to the stratified storage tank anymore, because of the higher temperatures in the storage. The PVT collector then works just only as PV module.

6.4. Full cost calculation:

Full cost calculations of the 4 proposed heating systems were done based on the annuity method in VDI 2067 (VDI 2067, 2000). All the heating systems were realized with the same area of 23.8 m² PV/PVT. The cost calculation depends on the assumed component and energy prices (see tables 3 & 4). For all 4 proposed systems an economical benefit can be reached by the application of load shifting (see figure (7)). With in the future further falling feed in tariffs for PV current, this benefit will get bigger. It can be seen in figure (7) that in the reference system the biggest economical benefit can be achieved. This is due to the effect that loads shifting in the PVT systems results in smaller heat gains of the thermal part of the PVT collector, what restricts the overall benefit. Additionally to the full costs of the systems also the CO2-emission of the individual case are displayed, so the full costs can be better classified.

When the systems itself are compared, an economical advantage of the AWHP+PV system over the 3 PVT systems can be observed. This is due to 2 reasons: At first, the investment costs at present of the PVT collectors compared to the PV modules are 57 % higher per kWp. And at second, the load shifting process - as has been stated numerous times in this paper - minimizes the thermal input of the PVT collectors in the systems. However, PV modules are an advanced industry product, where the PVT collectors are produced at present in low quantities and therefore have more cost reduction potential. To get economically competitive in the proposed applications, the prices for the PVT collectors had to fall to a level of 14 % above the PV modules per kWp. Of the three PVT systems, system 3 is admittedly the system with the highest investment cost, but presents in the full cost calculation as the cheapest system, because of the higher efficiency of the system compared to the systems 1 and 2. Therefore if a system with PVT is realized, system 3 can be recommended as hydraulic scheme for the realization.

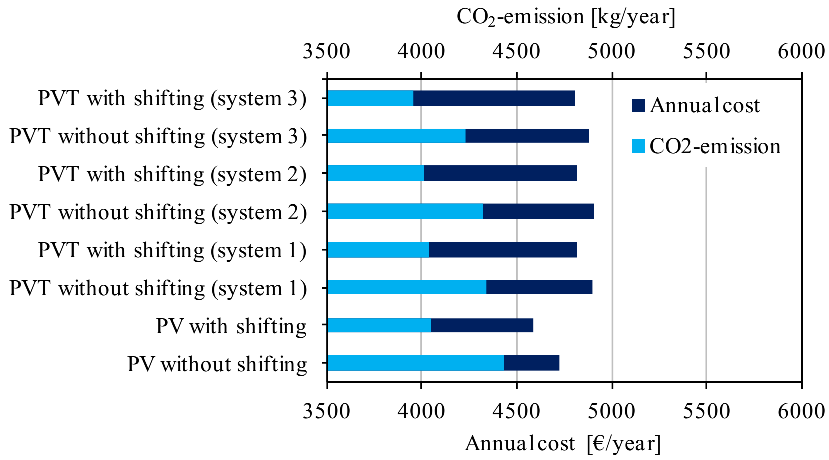

Fig. 7: Annuity costs and CO_2-emission for the proposed heating systems.

7. Conclusions

In this study different possibilities to integrate PVT collectors in an air to water heat pump system have been evaluated. The results of these systems have been compared to each other and to the results of an air to water heat pump system combined with a PV system. A control to store local generated PV energy as heat (load shifting) has been applied for all the systems. The results show, that the usage of PVT instead of PV panels can reduce the primary energy consumption (2.2 % from system 3 compared to the reference, both with load shifting). Whereby the effect of PVT is restricted by the load shifting control, due to the reduced thermal efficiency of the PVT collectors with increasing temperatures of the storage tank. The results present system 3 with 2 as the most efficient hydraulic system of the three PVT systems. However, the differences between the systems are small. The full cost calculations show, that according to the current European market, using (unglazed) PVT instead of PV panels in the presented framework is at present not economically justified. However, if the prices of unglazed PVT would fall to a level of about 14 % above PV per kWp electrical power, the PVT collectors become economically competitive in the proposed systems.

8. References

Abdul-Zahra, A., Faßnacht, T., Wagner, A., 2014. Thermal storage tanks and the building as storage for locally generated renewable electricity, Gleisdorf SOLAR Conference 2014.

Drück, H., 2006. MULTIPORT Store - Model for TRNSYS Type 340. Version 1.99F. Universität Stuttgart, Institut für Thermodynamik und Wärmetechnik.

Dott, R., Haller M., Ruschenburg, J., Ochs, F. and Bony J., 2012. The reference framework for system simulation of the IEA SHC Task44/HPP Annex38: Part B: Building and space heat load. Technical Report IEA-SHC Task44 Subtask C, www.iea-shc.org/task44.

EnEV 2009, 2009. EnEV 2009 - Energieeinsparverordnung für Gebäude. German directive.

Faßnacht, T., 2015. Moderne Regelungsansätze für Solarsysteme mit integrierter Wärmepumpe zur Gebäudeheizung, PhD thesis (Manuscript; to be published), Universität Stuttgart.

Harry, W., 2014. Recent Facts about Photovoltaics in Germany. Fraunhofer Institute for Solar Energy Systems ISE, Germany.

Malenkovic, I., Eicher, S. and Bony, J. 2012. Definition of main system boundaries and performance figures for reporting on SHP systems. Technical Report IEA-SHC Task44 Subtask B, www.iea-shc.org/task44.

Project BiSolar-Wärmepumpe, Solare Gebäude-Wärmeversorgung mit unverglastem photovoltaisch-thermischen Kollektor, Erdsonde und Wärmepumpe für 100% solaren Deckungsanteil. ISFH Hameln, http://www.isfh.de/institut_solarforschung/bisolar-waermepumpe.php (last accessed on 26.01.2015)

Standard DIN EN 12975-2, 2006. Thermische Solaranlagen und ihre Bauteile – Kollektoren – Teil 2: Prüfverfahren, Deutsche Fassung EN 12975-2.

Standard DIN EN 60904-8, 1998. Photovoltaische Einrichtungen, Teil 8: Messung der spektralen Empfindlichkeit einer photovoltaischen (PV) Einrichtung. Deutsche Fassung EN 60904-8.

Standard prEN 15203 / 15315, 2006. Energy performance of buildings - Overall energy use, CO_2 emissions and definition of energy ratings.

Solar Energy Laboratory, 2012. University of Wisconsin Madison: TRNSYS 17 – A Transient System Simulation Program, http://www.trnsys.com.

Stegmann, M., 2011. PVT-Kollektormodell. Presentation in Workshop Project BiSolar-WP, Emmerthal, 20.03.2011. http://www.isfh.de/institut_solarforschung/files/03_bisolarwp_modellentwicklung.pdf (last accessed 03.07.2014).

Solimpeks Solar GmbH. Effizienz im Doppelpack Gleichzeitig Wärme und Strom gewinnen. http://www.stsol.de/downloads/volther-powervolt1.pdf (last accessed on 29.01.2015).

Skoplaki, E., Palyvos, J.A., 2009. On the temperature dependence of photovoltaic module electrical performance: A review of efficiency/power correlations. Solar Energy 83, 614–624.

VDI-Richtlinie 4655, 2008. VDI 4655 Referenzlastprofile von Ein- und Mehrfamilienhäusern für den Einsatz von KWK-Anlagen, Guideline, Verein Deutscher Ingenieure.

VDI-Richtlinie 2067, 2000. Economic efficiency of building installations - Fundamentals and economic calculation, Guideline, Verein Deutscher Ingenieure.

Wetter, M., Afjei, Th., 1996. TNRSYS Type 401 Kompressionswärmepumpe inklusive Frost und Taktverluste. Zentralschweizerisches Technikum Luzern.