Decarbonizing Heating Supply Systems in Existing Single-family Houses Through PVT - Heat Pump Systems

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Abstract

Photovoltaic - Thermal (PVT) collectors are a silent, invisible and almost everywhere available heat source for heat pumps to decarbonize the existing building stock. The ongoing research project investigates PVT - assisted heat pump systems in the building sector, aiming to increase market awareness of this technology. The paper presents the simulative comparison of different heat supply systems for an existing state single-family house. The results show that the PVT - heat pump achieves higher efficiency than an air-source heat pump. With 30 m² PVT provided with an optimized (air) heat exchanger, the heat pump achieves ≈14 % higher efficiency than the air source heat pump (seasonal performance factor 3.59 PVT - heat pump to 3.10 air source heat pump). PVT (30 m²) as a sole heat source for the heat pump system reduces the CO_2 emissions up to 49 % compared to a condensing gas boiler and 25 % compared to air-source heat pumps. Combining PVT with borehole heat exchanger (BHE) with brine-water heat pump systems reduces 54 % CO_2 emissions compared to the gas boiler while simultaneously enabling smaller dimensioning of BHE with summer regeneration with PVT heat. Hence the results confirm the good performance of the PVT as a single or additional heat source for heat pumps. The paper also shows that PVT's design and performance are more important if it works as a sole heat source than if it assists a borehole heat exchanger.

Keywords: Photovoltaic-Thermal (PVT) collector, TRNSYS Simulation, Monitoring, heat pump system

1. Introduction

The heat supply to buildings constitutes about 40 % of the total energy demand in Germany. Around half the energy for heat generation in Germany is currently provided by natural gas (BDH 2021). According to BDH (Federation of German Heating Industry), around half of all heating systems in Germany are outdated (BDH 2021). Not only with a view to the climate goals and the necessary reduction of CO_2 emissions but the current political situation between Ukraine and Russia and a shortage of gas supplies to Europe strongly encourage us to accelerate more into renewable energy, especially in the heating sector. Heat pump (HP) systems offer a promising opportunity to replace conventional fossil fuel-based heating systems for space heating and domestic hot water (oil and gas boilers). Besides renovating the buildings to achieve low supply temperatures, searching for a suitable heat source is challenging. Photovoltaic-thermal (PVT) collectors can be used as a direct or additional heat source for brine-water heat pumps. PVT collectors combine a solar thermal collector and a photovoltaic module in a single component, simultaneously generating power and heat from the same area. They are silent, invisible, and feasible almost everywhere. Therefore, PVT can be a crucial technology for future energy supply systems by maximizing the fraction of local renewable energy source utilization and making a decisive contribution to the realization of the climate-neutral building stock.

The ongoing project "integraTE" investigates PVT collectors with heat pumps and tries to increase market awareness of this technically attractive energy supply system for the building sector. PVT collectors can be used as a single heat source for the heat pump or as an additional heat source with ground heat exchangers, like borehole heat exchangers (BHE). In the project, ten demonstration systems are part of ongoing monitoring, as presented in detail in Helmling et al. (2022). Among all the systems, five systems use PVT collectors as a single heat source for the heat pump, and the remaining five systems combine the PVT with at least one additional heat source, such as a borehole heat exchanger (BHE). Apart from the monitoring, the project aims to carry out detailed simulative investigations of different energy supply systems. The first simulation study

doi:10.18086/eurosun.2022.07.01 Available at http://proceedings.ises.org

compares various energy supply systems for a new single-family with a PVT - heat pump, and the detailed results are presented in Chhugani et al. (2023).

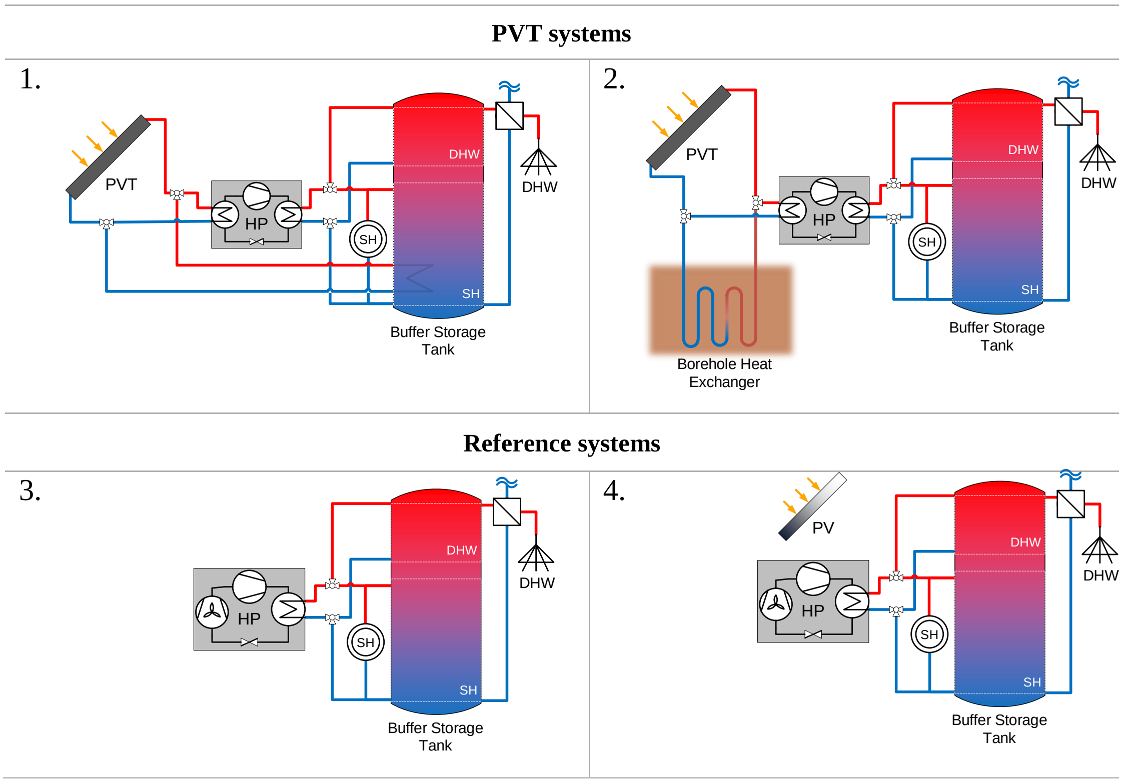
This paper investigates different energy supply concepts for an existing single-family house for the German climate and mainly focuses on PVT-assisted heat pump systems. The simulation study compares two PVT systems and six reference systems. As for the PVT- heat pump systems, PVT collectors are used as a single and additional heat source for heat pumps. All simulated systems are listed below and shown in Fig. 1.

- PVT - heat pump systems
    1. PVT - heat pump
    2. PVT - borehole heat exchanger (BHE) - heat pump

- Reference heat pump systems
    3. Air source heat pump
    4. PV - air source heat pump
    5. Borehole heat exchanger - heat pump
    6. PV - borehole heat exchanger - heat pump

- Gas heating systems
    7. Gas condensing boiler
    8. Solar thermal collectors - gas condensing boiler

The contribution also includes a description of different boundary conditions, system components, and control strategies of the simulations. The simulations are performed using the software TRNSYS v17.01.0028. Two different PVTs collectors (uncovered or WISC: Wind and Infrared Sensitive Collector) are analyzed regarding system performance with heat pumps for sensitivity analysis. The system evaluation is carried out based on two assessment criteria: CO_2 emissions and seasonal performance factors.



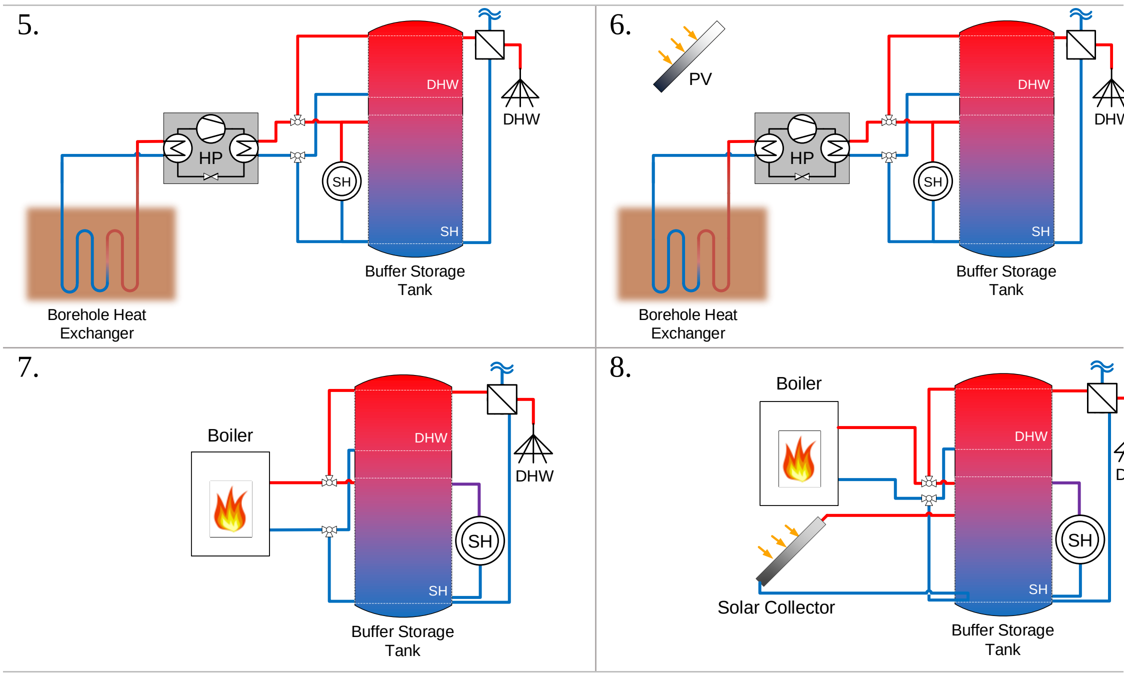


Fig. 1: Simulated PVT- heat pump and reference systems

2. Simulation boundary conditions and methodology

2.1 Building

The reference IEA SHC Task 44 single-family house (SFH100) has been chosen for the simulation, which corresponds to an existing building (built or renovated 25 years ago) for European Climate. In Task 44, the building heating demand was investigated for the reference climate Strasbourg, with a heating demand of 100.2 kWh/(m²·a) and all boundary conditions of the building described in Dott et al. (2013). In the project "integraTE", the heating demand of this building is investigated for the German location Wuerzburg with the Meteonorm one-minute weather data. It is approx. 108 kWh/m²a, which is supplied with radiators, and the heating characteristic curve has a maximum supply temperature of 55 °C

2.2 Household electricity

The photovoltaic-thermal collectors provide electricity and heat; therefore, the household electricity profile has been defined and presented. For this purpose, the (VDI-Richtlinie 4655:2021) electrical profile for an existing single-family house is used, with annual electricity consumption of ≈ 4039 kWh. The yearly electrical profile is shown in Fig 2.

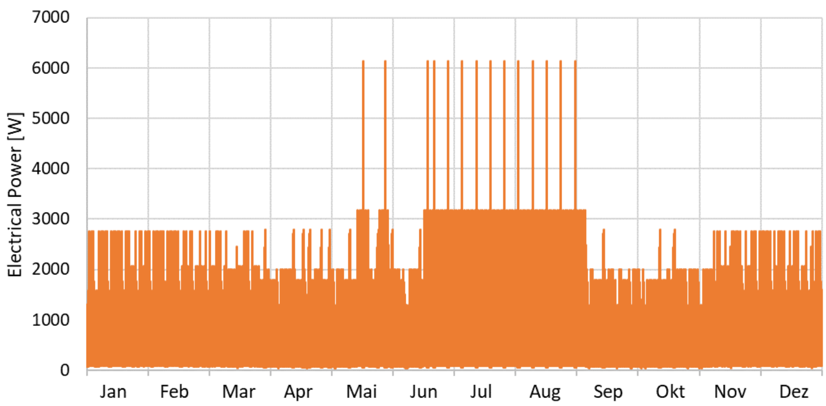


Fig 2: Household electricity demand of the existing SFH according to VDI 4655

2.3 Domestic hot water

The tap profile for domestic hot water (DHW) demand of the single-family house is derived from IEA SHC Task 44 (Haller et al. 2013). The energy demand of the DHW is approx. 5.8 kWh/d (15 kWh/m²a), with a total daily hot water demand of 145 l/d and the hot water tap at 45 °C without hot water circulation. The DHW profile is shown in Fig. 3. An instantaneous water heater efficiently delivers DHW to the building, which has a UA value according to (eq. 1).

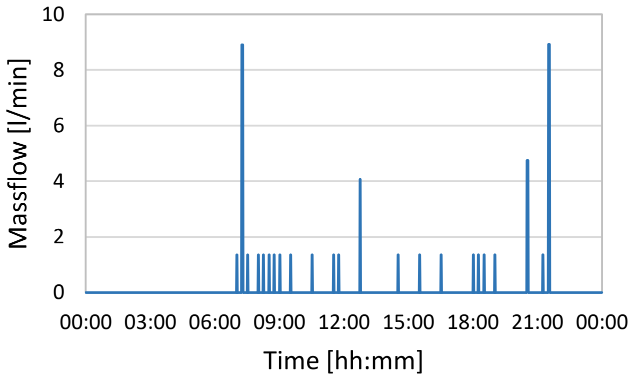


Fig. 3: Domestic hot water demand (DHW) of the building at 45°C

$$UA = -1{,}8\frac{W/K}{(kg/min)^2} \cdot \dot{m}_{sec}{}^2 + 240\frac{W/K}{kg/min} \cdot \dot{m}_{sec} + 600\frac{W}{K} \qquad \text{(eq. 1)}$$

2.4 Photovoltaic - Thermal (PVT) collectors

As mentioned before, two different market-available PVT collectors are used for the sensitivity analysis in the study. The first collector is an uncovered/WISC PVT collector with a finned air heat exchanger on the back side, developed explicitly for heat pump applications. The thermal parameters of the collector are determined using outdoor tests (Giovannetti et al. 2019) and compared to TRNSYS simulations, especially under frost conditions (Chhugani et al. 2020). The second PVT collector is a standard uncovered/WISC PVT collector without fins, whose parameters are taken from the Solar Keymark test certificate. Both collector parameters are shown in Tables 1 and 2.

For the simulation of the PVT collector in TRNSYS, type 203 has been used, which was explicitly developed for uncovered PVT collector simulations (Stegmann et al. 2011). This model combines two performance models, the thermal part of the model is based on (EN 12975-2:2006), and the empirical effective solar cell model defines the electrical side of the collector (PV module) by Wagner (2010). For the dynamic PVT simulations, collector parameters are required from performance tests and manufacture standard data sheets. Both characteristic models are interconnected for the calculation of correct PV cell temperature. The detailed PVT model is described in (Stegmann et al. 2011).

For the configuration of PVT to heat pump (in Fig. 1(1)), the PVT collector is used as the only heat source for the heat pump, and in summers if the PVT temperature is higher than the buffer storage tank, then PVT heat is used directly to storage tank. Both PVTs in simulations are regularly defrosted to account for model uncertainties below 0 °C as explained in (Chhugani et al. 2020). In the PVT with borehole heat exchanger (BHE) to heat pumps (in Fig. 1(2)) configuration, PVT is only used if the collector temperature is 5K higher than BHE, and on sunny days BHE is regenerated with PVT heat when the heat pump is not running, and PVT temperature remains higher than BHE.

Tab 1: Thermal PVT parameter sets (MPP-related)

	η_0 [-]	c_1 [W/(m²·K)]	c_3 [J/(m³·K)]	c_4 [-]	c_5 [kJ/(m²·K)]	c_6 [s/m]
PVT (WISC) with fins	0.532	19.08	3.69	0.434	26.05	0.067
Standard PVT (WISC)	0.570	11.02	4.80	0.620	42.20	0.011

Tab 2: Electrical PV parameter at Standard Test Conditions (STC)

	P_{mpp} [Wp]	A [m²]	η_{el} [-]	V_{mpp} [V]	I_{mpp} [A]	V_{oc} [V]	I_{sc} [A]	TC [%/K]
PVT (WISC) with fins	340	30	17.5	37.6	9.05	48.0	9.45	-0.39
Standard PVT (WISC)	300	30	18.3	32.6	9.19	39.9	9.77	-0.39

2.5 Brine water heat pump

For the PVT to heat pump (HP) simulation, a modulating brine-to-water heat pump with a thermal capacity of 12.46 kW and a COP of 4.13 at B0/W35 has been used. This HP is suitable for integration with PVT collectors as the only heat source and can operate down to a minimum inlet temperature of -15 °C on the evaporator side. Fig. 4 shows the characteristic curve of the heat pump. If the temperature falls below the minimum source inlet temperature, the integrated auxiliary heater (12 kW) in the heat pump takes over the charging of the storage tank as a bivalent-alternative operation. For compressor protection, as in actual heat pump operation, the heat pump has a minimal pause time of 20 min.

The TRNSYS type 401 is used for heat pump simulations developed by (Afjei and Wetter M. 1997). This type can simulate different heat pumps, such as air-source and brine-water. The heat pump model is based on biquadratic polynomials for condenser power and compressor power calculated from the heat pump characteristic data obtained from experiments, as shown in Fig. 4(b) for the heat pump used in this simulation. The modulation is modeled with three instances of type 401 in parallel and linear interpolation, as proposed by (Hüsing und Pärisch 2020).

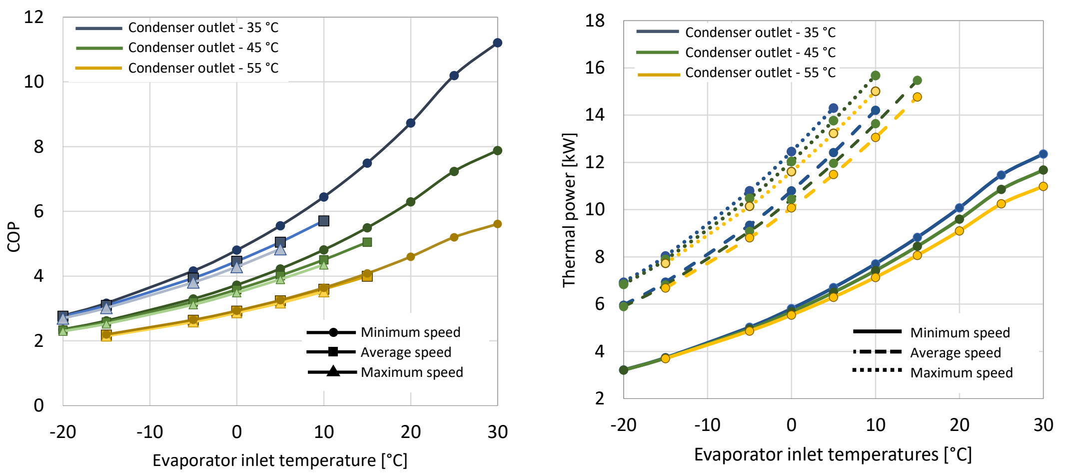


Fig. 4: Characteristics data of the heat pump, (a) coefficient of performance (b) thermal power, at different evaporator inlet temperatures (x-axis) and condenser outlet temperatures (blue 35 °C, green 45 °C, yellow 55 °C) for three different compressor speeds

2.6 Borehole heat exchanger (BHE)

Besides, BHE as a single heat source for heat pumps, a combination of BHE and PVT with heat pumps is also simulated and investigated. They are connected in parallel, and the higher temperature source is preferred when the HP is running. The reason for these simulations is the high efficiency and the opportunity to shorten the required length of BHE by regeneration of the ground in the summer through PVT. For the simulation, a 120 m deep BHE was simulated with 30 m² of PVT and 180 m BHE as the only heat source. TRNSYS Type 451 was validated through the experimental system at ISFH for TRNSYS simulation (Pärisch et al. 2015). The simulation with a borehole heat exchanger runs for two years, and the second year's simulated result is evaluated and presented here in the paper.

2.7 Air source heat pump

The air-source heat pump of the reference system has a thermal heating capacity of 11.2 kW and a COP of 3.5 at A2/W35, including defrosting losses. TRNSYS type 401 (Afjei und Wetter M. 1997) is also used for the air source heat pump simulations with the built-in COP-reduction for defrosting. However, the air-source heat pump modeling considers other electrical stand-by losses and thermal losses due to the frosting processes of the air heat exchanger outdoor unit. These losses are simplified in type 401 by a modified Gauss function representing the percentage reduction in COP as a function of the outdoor temperature, and the method is explained in Afjei and Wetter M. (1997). The COP reduction function of the simulated heat pump in this paper is derived according to experimental investigations from ISFH. This COP reduction function at different relative humidity levels is presented in Chhugani et al. (2023). Moreover, as in a real system, de-icing can occur every 30 to 60 minutes on colder winter days; at that time, the heat pump can no longer supply energy to the building, and then the electric rod often starts; this effect cannot be simulated with type 401.

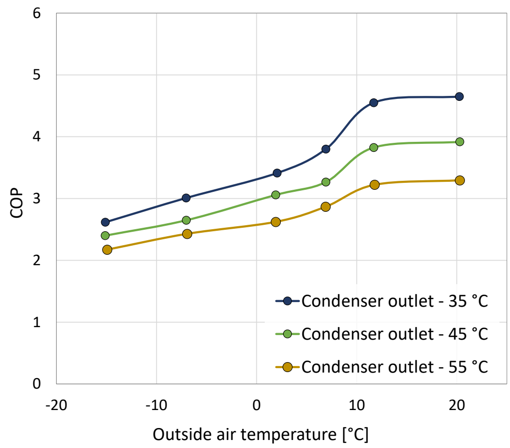


Fig. 5: Air source heat pump coefficient of performance for different air temperatures (x-axis) and condenser outlet temperatures (35 °C, 45 °C, 55 °C) with defrosting losses

2.8 Buffer storage tank

The building is simulated with a buffer tank of 560 liters on the sink side of the heat pump. Three immersion temperature sensors are used for the controller. The upper temperature (relative height 0.9) sensor records the temperature of the standby section for domestic hot water demand; the middle-temperature sensor (relative height 0.5) for the space heating. Furthermore, there is a solar part for direct solar gains in the summer and defrosting in the winter (rel. height 0.2). For the dynamic simulation of the thermal buffer storage tank, stratified fluid storage tank TRNSYS Type 340 has been used (Drück 2006).

The simulation is carried out with a "PV-based control strategy", where the storage tank is charged with two different temperature setpoints in this strategy. If the total irradiance on the collector plane is higher than 500 W/m², the heat pump heats the domestic hot water zone to a maximum temperature of 60 °C with a hysteresis of -3 K. Afterwards, if irradiance is still higher than 500 W/m², the bottom part of the storage tank for the space heating is charged. This bottom layer is heated up 10 K higher than the heating characteristic for the SFH100, according to (Dott et al., 2013) with -3 K hysteresis. And when the irradiance drops below 500 W/m², the heat pump heats the domestic hot water zone at a maximum of 55 °C with a -5 K hysteresis. The space heating zone is charged based on the outside temperature according to the heating characteristic curve for the SFH100 with -3 K hysteresis with a maximum temperature of 55 °C at -14 °C.

2.9 Condensing gas boiler

The gas boiler is a classic condensing modulating boiler with a nominal heating power of 25 kW and water content of 7.3 liters. The boiler's efficiency at nominal load is 96.59 % based on a higher heating value. The boiler is simulated with the Type 204 developed at ISFH and extensively presented in (Glembin and Rockendorf 2010).

2.10 Solar collectors

The next reference system is a solar combi system equipped with the same gas condensing boiler as explained above and an additional 15 m² solar thermal system. The system combines a 1050 l buffer storage tank to use high solar potential. The parameters of the solar flat plate collector are shown in Table 3.

Tab 3: Efficiency parameters of the solar flat plate collector used for the reference system (Solar Keymark Test)

	η_0 [-]	a1 [W/(m²K)]	a2 [W/(m²K²)]
Flat plate solar collector	0.81	3.757	0.014

The secondary pump (between the heat exchanger and storage tank) switches on when the heat exchanger input temperature on the primary side exceeds the lower storage tank temperature by 7 K. The operating mode of the pumps is low-flow with 20 kg/(m²·h). The secondary pump is switched off when the difference falls below 5 K.

2.11 Key performance indicators (KPIs)

The heat supply systems presented in the paper are evaluated and analyzed based on different key performance indicators (KPIs). Two categories characterize these KPIs; 1) Environmental indicators and 2) Energy-related indicators.

- Environmental indicator

The CO_2 emissions of all the systems are calculated as the sum of the energy consumption values (gas or electricity) by the respective energy supply system, each multiplied by the corresponding emission factors according to the German Building Energy Act (GEG). The CO_2 emission factors for the two energy sources, natural gas and electricity according to GEG, are given below and used in the calculation with equation 2.

$$CO_{2,Emissions} = Final\ energy\ consumption\ (Gas/Electricity) \cdot x_{CO_2} \qquad \text{(eq. 2)}$$

x_{CO_2}: CO_2- Emission factors (x_{CO_2}) in kg CO_2-Equiv. /kWh
Natural gas: 0.24 kg/kWh,
Electricity: 0.56 kg/kWh (electricity taken from Grid)
Electricity: 0.0 kg/kWh (generated by PV/PVT panels and consumed by the system)

- Energy-related indicators

In order to analyze the performance of the systems, two different seasonal performance factors SPF_{bSt} and $SPF_{bSt}^{(Grid)}$ are used and explained in equations 3 to 6 for different systems. The performance factors have been adjusted according to the individual system, but reference is taken from Task 60 and Task 44, as explained in (Malenković et al. 2012; Zenhäusern et al. 2020). Although the system boundary "before storage" SPF_{bSt} gives the better results and doesn't consider the overall system losses (Pärisch et al. 2013); it is also taken for our simulations because it allows comparison to the field tests performed by Fraunhofer ISE, similarly explained in (Helmling et al. 2022). The different heat pump systems are presented with their respective square views (Fig. 6 and Fig. 7) for simplification.

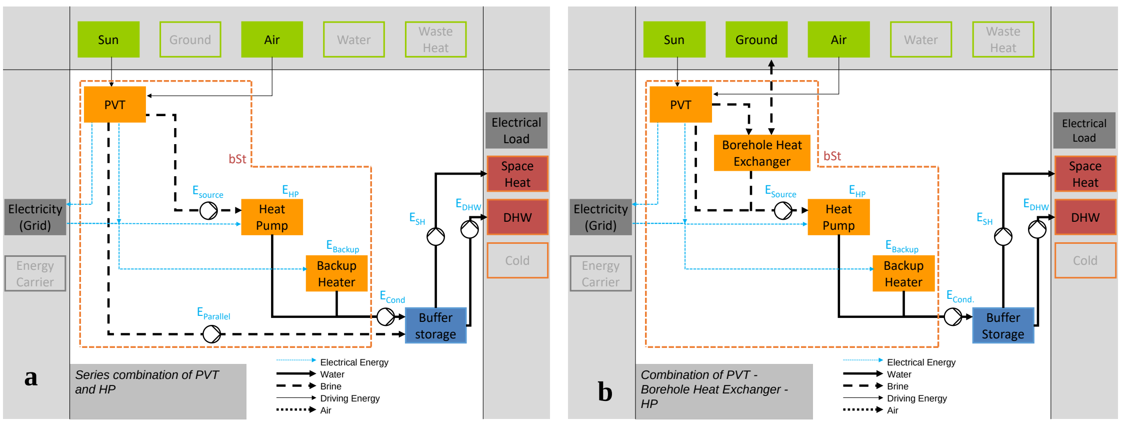


Fig. 6: Square-views of different heat pump systems (a) PVT - heat pump (b) PVT - BHE - heat pump for boundary bSt (before storage in dashed line)

$$SPF_{bSt} = \frac{\int(\dot{Q}_{HP} + \dot{Q}_{Backup} + \dot{Q}_{PVT,parallel})\,dt}{\int(\dot{E}_{HP} + \dot{E}_{Backup} + \dot{E}_{Pumps})\,dt} \quad \text{(eq. 3)}$$

$$SPF_{bSt}^{(Grid)} = \frac{\int(\dot{Q}_{HP} + \dot{Q}_{Backup} + \dot{Q}_{PVT,parallel})\,dt}{\int_{>0}(\dot{E}_{HP} + \dot{E}_{Backup} + \dot{E}_{Pumps} - \dot{E}_{PVT\_el\_Self})\,dt} \quad \text{(eq. 4)}$$

For the PVT - heat pump system in Fig. 6(a), SPF_{bSt} is the ratio of the heat quantities supplied to the buffer storage by the heat pump ($\dot{Q}_{HP}$), the auxiliary heating ($\dot{Q}_{Backup}$) and the PVT direct charging as well as defrosting ($\dot{Q}_{PVT,parallel}$) divided by the electrical energy consumed within this system boundary, and explained in eq. 3. $\dot{E}_{HP}$ is the electrical energy of the heat pump, $\dot{E}_{Pumps}$ is the pump energy of source pumps, and for PVT direct charging/defrosting pump. Besides, $\dot{E}_{Backup}$ is the electrical energy of the auxiliary heater.

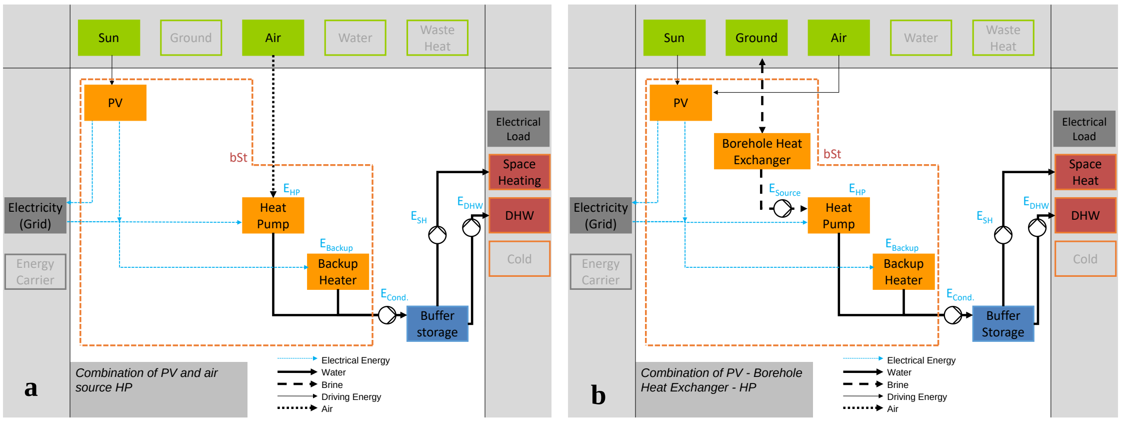


Fig. 7: Square-views of different heat pump systems (a) PV - Air source heat pump (b) PV - BHE - heat pump for boundary bSt (before storage in dashed line)

SPF_{bSt} for rest of the heat pump systems for Fig. 6 (b) and Fig. 7(a,b) is calculated using eq. 5, which considers energy supplied by the heat pump ($\dot{Q}_{HP}$) and the auxiliary heating ($\dot{Q}_{Backup}$) to the buffer storage and devided by the electrical energy consumed within its system boundary.

On the other hand, $SPF_{bSt}^{(\mathrm{Grid})}$, which considers self-consumed PVT/PV electricity in the bSt boundary, is calculated using eq. 4 (for PVT - heat pump system in Fig. 6 (b)) and eq. 6 (for all the remaining heat pump systems). This means that the generated electrical power of PVT/PV is used simultaneously for the electrical consumption of the heating system (simulation time step = 1 min) without battery storage.

$$SPF_{bSt} = \frac{\int(\dot{Q}_{HP} + \dot{Q}_{Backup})\,dt}{\int(\dot{E}_{HP} + \dot{E}_{Backup} + \dot{E}_{Pumps})\,dt} \quad \text{(eq. 5)}$$

$$SPF_{bSt}^{(Grid)} = \frac{\int(\dot{Q}_{HP} + \dot{Q}_{Backup})\,dt}{\int_{>0}(\dot{E}_{HP} + \dot{E}_{Backup} + \dot{E}_{Pumps} - \dot{E}_{PVT/PV\_el\_Self})\,dt} \quad \text{(eq. 6)}$$

For the heat pump systems according to configurations 3 and 5 from Fig. 1, where there is no PV/PVT available then the $SPF_{bSt}^{(\mathrm{Grid})}$ is not calculated.

Additionally, in the $SPF_{bSt}^{(Grid)}$ factor, produced PVT/PV electricity is used for the heat pump system with the first priority, which increases self-consumption of PVT/PV electricity for the heat pump system hence the $SPF_{bSt}^{(Grid)}$ upsurges. However, in reality, household electricity should be given first priority because household electricity is more expensive than heat pump tariff. Many heat pump suppliers use this approach to make their products attractive. In order to make things more transparent, two different electricity distribution priorities have been simulated and compared in this simulation study. In priority-A, the heat pump system benefits more from PVT/PV electricity regardless of household demand, and with priority-B, the benefit enormously depends on the household energy demand.

Priority-A:
1. Heat pump system
2. Household electricity
3. Grid feed-in

Priority-B:
1. Household electricity
2. Heat pump system
3. Grid feed-in

3. Results

Fig. 8 shows the seasonal performance factors (SPF) of the different simulated heat pump systems. The simulation result with Priority-A is shown in Fig. 8 (a), and that with Priority-B is illustrated in Fig. 8 (b).

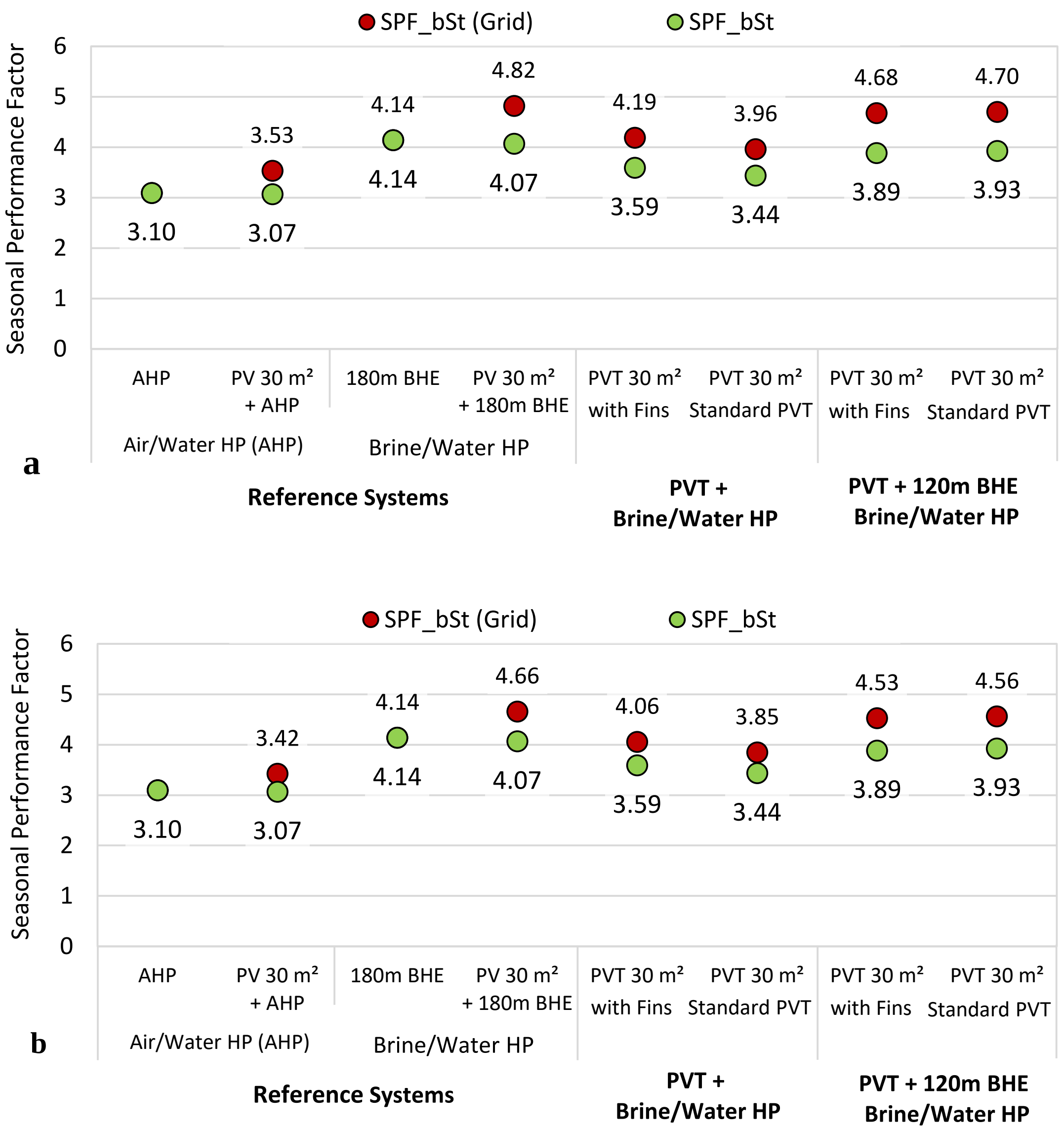


Fig. 8: SPF (Seasonal Performance Factor) of different systems (a) with Priority-A (heat pump as a first priority) (b) with Priority-B (household electricity as a first priority)

The difference between these two electricity priorities is visible in the $SPF_{bSt}^{(Grid)}$ factor. However, the discrepancy between these two priorities is very low, approx. 3% for any heat pump systems where PV/PVT electricity is available and directly used for the heating system. This indicates that produced PVT/PV can be used with any priorities. However, there is no battery storage here; if the battery storage is considered, the results might be different because the stored electricity will be first used for household electricity, and the rest will only be used for heat pumps.

With priority-A, the direct comparison of the air-source HP with PVT to HP proves that systems PVT systems are more efficient. The PVT with fins (PVT 30 m²) achieves SPF_{bSt} of 3.59 against SPF_{bSt} of 3.10 for the air-source heat pump. The same 30 m² PVT - heat pump system reaches $SPF_{bSt}^{(Grid)}$ of 4.19 compared to $SPF_{bSt}^{(Grid)}$ of 3.53 with 30 m² of PV - air source heat pump. A heat pump with 180 m deep BHE achieves SPF_{bSt} of 4.14, and combining 30 m² of PV with the geothermal heat pump system boosts the $SPF_{bSt}^{(Grid)}$ to 4.8.

On the other hand, 30 m² PVT with 120 m deep BHE achieves $SPF_{bSt} \approx 3.9$ and $SPF_{bSt}^{(Grid)} \approx 4.7$ regardless of PVT collector. Hence, it is crucial to understand that the PVT combination with BHE opens the possibility of reducing BHE length (here reduced by ≈ 33 %, from 180 m to 120 m) without significantly affecting system efficiency. This aspect becomes economically more relevant for larger systems with two or more boreholes. On the other hand, ground source regeneration via PVT heat generally ensures a sustainable system operation, and it can compensate for planning uncertainty even for small BHE installations.

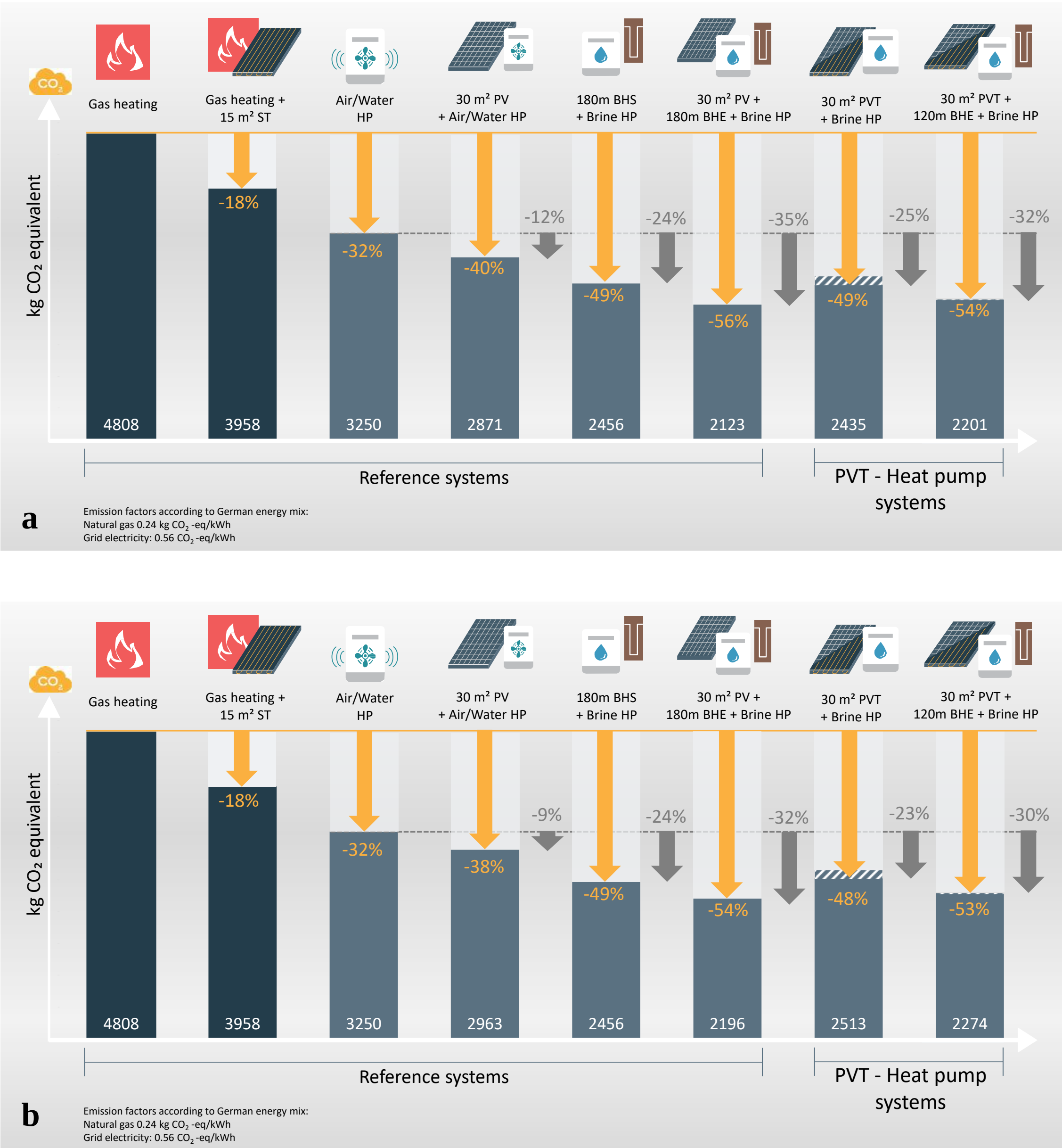


Fig. 9: CO_2 emissions of different simulated heat supply systems (a) with Priority-A (heat pump as a first priority) (b) with Priority-B (household electricity as a first priority)

Fig. 9 shows the CO_2 emissions with different energy supply systems with different electricity distribution priorities and calculated according to equations 2. The calculations of CO_2 emissions for the heat pump systems are carried out with a PV-based control strategy and based on electricity taken from the grid only for the heating system. As shown in Fig. 9, the highest amount of CO_2 emissions is produced with a condensing gas boiler with 4808 kg CO_2 equivalent, as expected. The solar thermal combi system (15 m²) reduces CO_2 emissions by 18 %. The heat pump systems show significant potential for CO_2 reduction compared to the gas boiler. An air-source HP reduces CO_2 emissions by 32 %, whereas PV with an air-source heat pump reduces emissions by 40 % with Priority-A and 38% with Priority-B. There is also substantial potential for CO_2 reduction by replacing the heating system with PVT - heat pump systems. PVT with fins (30 m²) with heat pump reaches CO_2 savings of 49 % (B: 48 %), same as 180 m BHE - heat pumps. In general, the PVT collector coupled with the HP system offers high CO_2 saving potential and represents an attractive alternative to the PV-air source or the geothermal heat pump.

On the other hand, 30 m² PVT with BHE (120m) with heat pumps are proven to be similarly efficient as 30 m² PV with BHE and heat pump. PVT with BHE combination reduces CO_2 emissions by 54 %, whereas PV wot BHE decreases CO_2 emissions by 56% (With Priority A). The hatched area shows the variation between the two PVT designs. Unlike the system used as an only heat source, the PVT design is not essential for the investigated combination of PVT and BHE.

4. Conclusion

The ongoing research project “integraTE” aims to comprehensively assess PVT- heat pump systems and increase market awareness of this new technology for the building energy supply sector. Detailed simulative investigation in the project generates information and allows understanding of the performance of this PVT - heat pump systems for existing German buildings.

The following points summarize the essential findings of the simulations:

- The seasonal performance factors (SPF_{bSt}) of PVT with fins as a single heat pump source is 14 % higher than that of PV to air source heat pump (both PVT and PV area 30 m² with priority-A)
- Considering PV electrical generation significantly enhances the system performance factor: with PV based control strategy without battery storage, the system reaches $SPF_{bSt}^{(Grid)}$ to 4.19 for 30 m² of PVT with fins for heat pump source with priority-A, whereas 30 m² PV - air source heat pump reaches only 3.53.
- PVT (30 m²) to heat pump system reduces the CO_2 emissions up to 49 %, dependent on the PVT design, compared to condensing gas boiler and 25 % CO_2 emissions reduction compared to air-source heat pumps.
- Combining PVT with borehole heat exchanger (BHE) in brine-water heat pump systems saves up to 54 % CO_2 emissions and reduces the required length of BHE from 180 to 120 meters, independently of the PVT design.

Summing up, direct coupling of PVT collectors with heat pumps as a single source (thermal side) achieves good system efficiency and represents a promising alternative to air source and geothermal heat pumps. PVT with boreholes (approx.≈33 % smaller) shows very good system efficiency, similar to PV with borehole systems. In the PVT-BHE configuration, PVT can favorably supply the heat to the heat pump directly or regenerate the ground source. Solar regeneration enables a sustainable operation of the BHE field by avoiding long-term cooling effects. It plays an important role, especially with larger installations, where smaller dimensioning of BHE is possible or required.

5. Acknowledgments

The presented work and results are part of the research project “integraTE - 03EGB0023” funded by the German Federal Ministry for Economic Affairs and Climate Action (BMWK) and supported by the Lower Saxony Ministry of Science and Culture. Furthermore. We thank our partners Fraunhofer ISE, IGTE of University Stuttgart and Solrico for the collaboration. Further, thanks go to blue energy systems (nD-Systeme), PA-ID Process, Architektur- und TGA-Planungsbüro Carsten Grobe, SunMaxx, Splus2, TripleSolar, and Consolar - Solare Energiesysteme for their financial support. The authors are grateful for the support and are responsible for the content of the publication.

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