Photovoltaic-Thermal (PVT) collectors as monovalent or bivalent heat sources for heat pumps in new multi-family houses

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Abstract

Photovoltaic-thermal (PVT) collector combines a solar thermal collector and a photovoltaic module in a single component, generating power and heat from the same area simultaneously. Hence PVT can be a crucial technology for the future energy supply of buildings. The paper presents a simulative study of PVT as source in heat pump systems for heat supply in multi-family houses. Results show that combining PVT collectors with borehole heat exchangers (BHE) offers the possibility of reducing and even eliminating BHE while achieving a high performance. The heat pump with a combination of PVT (80 m²) with one BHE with 150 m achieves a seasonal performance factor $SPF_{bSt}^{(Grid)}$ of 3.76. Additionally, the results confirm the good performance of PVT as a single heat source. Compared to PV with air-source heat pump, a PVT heat pump with 80 m² accomplishes $SPF_{bSt}^{(Grid)}$ of 3.45, whereas the maximum $SPF_{bSt}^{(Grid)}$ of PV (80 m²) to air source heat pump is 3.12.

Keywords: Photovoltaic-Thermal (PVT) collector, heat pump system, TRNSYS Simulation, multi-family house

1. Introduction

The energy supply for heating and cooling represents almost 50 % of the EU's total gross final energy consumption (Eurostat 2023). Renewable energy covered 22.9 % of the European heating and cooling consumption, and natural gas alone covered 34.3 % of the heating demand. Not only with a view to the climate goals and the necessary reduction of CO_2 emissions but the current political situation in Europe and gas supplies strongly encourage to accelerate more into renewable energy, especially in the heating sector. For this purpose, 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).

In Europe, the residential heat pump market has been steadily increasing for several years in most countries. Heat pumps are most common in new single-family houses, while the heat pump market share in multi-family buildings (MFHs) remains low. An important barrier to heat pump integration in MFHs is the difficult access to a suitable heat source. The majority of multi-family buildings are located in cities with high densities. Hence, access to geothermal sources for heat pumps could be complicated because the place to drill boreholes is missing, and air-source heat pumps are challenging to integrate because of the noise and efficiency issues. Photovoltaic-thermal (PVT) collectors represent a promising alternative as a single or additional heat source for brine-water heat pumps and have been receiving increasing attention both in research projects and on the market in the last years. PVT collectors convert solar radiation into useful heat and electricity; hence, higher solar energy is harvested with the same collector area. Therefore, PVT can maximize the fraction of local renewable energy source utilization.

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. The project aims at carrying out detailed simulative investigations of different system configurations and monitoring of ten demonstration plants, e.g. (Timilsina et al. 2023). The simulation results of various energy supply concepts for a single-family house and monitoring results of one of the demo plants are presented (Chhugani et al. 2023).

This paper aims to investigate PVT as a monovalent or bivalent heat source for heat pumps for new multi-family houses. One of the focuses of the study is to find out to what extent the BHE length can be reduced or entirely eliminated by using PVTs. Because in a new multi-family house normally requires 3 or 4 (total length of 300 m to 400 m) borehole heat exchangers (BHE). One of the case studies presented by Bockelmann (2021) on performance monitoring of ground source heat pump systems in two multi-family houses, where each MFH has 450 m boreholes length for the efficient heat pump operation.

Hence first goal of this paper is to combine BHE and PVT together as heat pump source to solve the problem of

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available space for drilling boreholes in cities/locations with high building densities. The second goal of the paper is to compare PVT with brine-water heat pump to PV with air-water heat pump systems. For the performance evaluation, two metrics have been used, which are CO_2-emissions and seasonal performance factors (SPF) and explained in equations 1 to 3.

2. Boundary conditions, system components and methodology

To investigate the behavior of the PVT heat pump system in a multi-family house (MFH), transient system simulations have been carried out using the software TRNSYS v17.0028 for the German location Wuerzburg. The detailed boundary conditions of the building and required components are explained in the following sections.

2.1 Building

The simulated MFH building has 4 floors, each featuring 2 flats with 84 m² living space. The south and north façades are equipped with windows. This multi-family house corresponds to the German building standard - KfW55 (KfW-Bankengruppe 2020), with a heating demand of approx. 21.1 MWh/a (specific 31 kWh/(m²·a)) and domestic hot water demand of approx. 6.7 MWh/a (specific 10 kWh/(m²·a)). The MFH was modeled as part of the ongoing BMWK-funded research project "Solar-VHF" and the detailed building description is presented in (Frick et al. 2021).

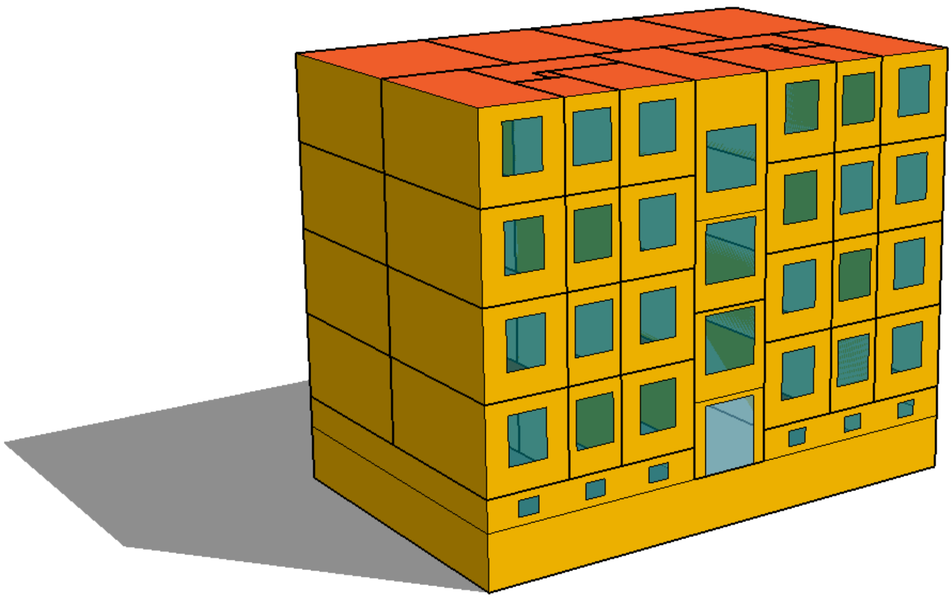

Fig. 1: Multi-story residential building containing 8 flats on 4 floors, each flat with 84 m² living space

The building features a two-pipes network for the heat distribution, which consists of one pair of pipes carrying heating water (flow and return) for both floor heating and domestic hot water. Each apartment in the building has a heat interface units (HIU). The supply temperature from the buffer storage tank to the HIU is maintained constant at 50 °C throughout the year to fulfill the domestic hot water demand.

The simplified hydraulic schematic of one of the simulated heating systems (PVT - heat pump system) is presented in Fig. 2. The system consists of a brine-water-heat pump, a borehole heat exchanger, PVT collectors, buffer storage, riser pipes, heat interface units in each apartment, a floor heating system (flow and return temperature 35/32 °C), a single-room air handling unit with heat recovery in each room except corridor, and external shading devices on all windows. The heat pump uses either PVT or the borehole heat exchanger (BHE) as a heat source. PVT additionally regenerate the BHE in the summer and can therefore reduce the BHE length.

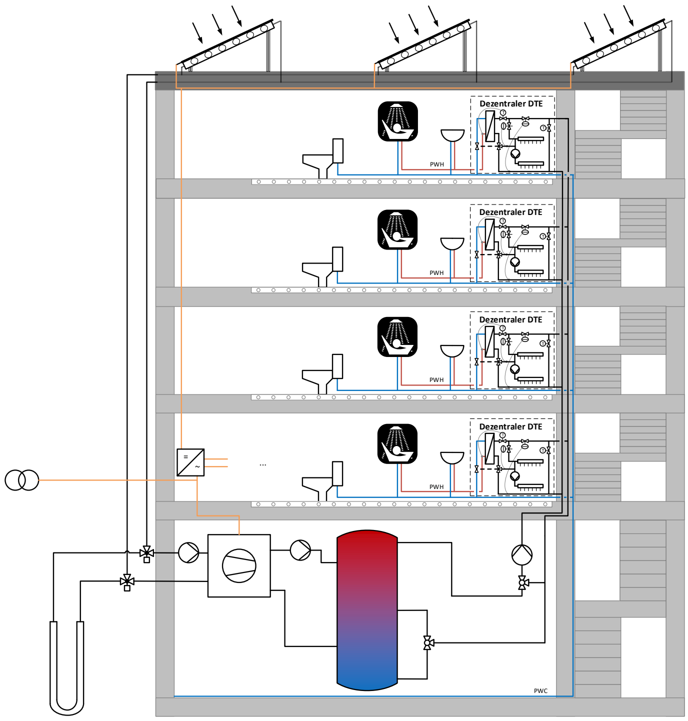

Fig. 2: Simplified hydraulic schematic of investigated multi-family house (MFH) integrated with PVT - heat pump systems

2.2 Brine water heat pump

The modulating brine-water heat pump with a thermal capacity of 12.46 kW and a COP of 4.13 at B0/W35 has been used in the study. This heat pump is suitable for integration with PVT collectors as well as geothermal sources as it can operate down to a minimum inlet source temperature of -15 °C up to 35 °C on the evaporator side.

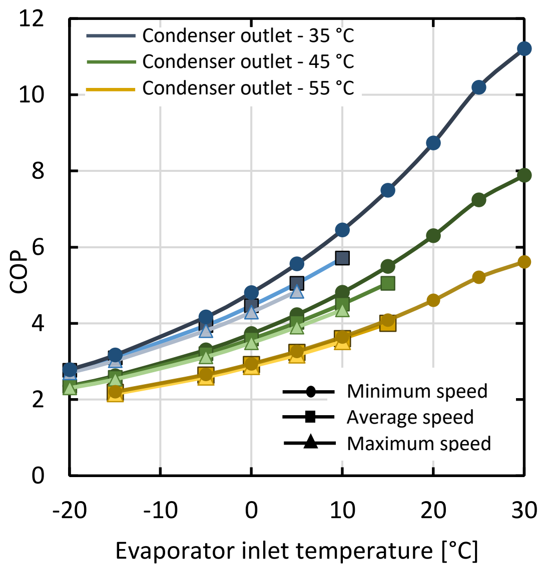

Fig. 3: Coefficient of performance of the heat pump used for the simulations at different evaporator inlet temperatures (x-axis) and condenser outlet temperatures (blue 35 °C, green 45 °C, yellow 55 °C) for three different compressor speeds

However, for the investigation in the paper, the heat pump is only used up to an inlet source temperature of -10 °C. If the source temperature falls below the minimum source inlet temperature, the integrated auxiliary heater (15 kW) in the heat pump takes over the charging of the storage tank as a bivalent alternative operation.

A study presented by Chhugani et al. (2020) confirms that changing the bivalence point from -10 °C to -15 °C, achieves 20 to 25 % higher Seasonal performance factors (SPF). The reason for not using the heat pump at very low evaporator inlet temperatures (i.e., -15 °C) for this investigation on MFH is that the heat pump's thermal power is insufficient to meet the building's thermal energy demand at very low inlet temperatures. This can be solved by using a heat pump with higher thermal power at lower evaporator temperatures or using bivalence parallel operation, where an auxiliary heater supports the partial thermal energy demand of the building. This strategy would also improve the system's efficiency; however, this is not investigated in this paper.

For compressor protection, as in actual heat pump operation, the heat pump has a minimal pause time of 15 min. The characteristics data of the heat pump is presented in the Fig. 3.

The TRNSYS type 401 developed by Afjei and Wetter (1997) is used to model the heat pump. 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 and compressor power calculated from the heat pump characteristic data obtained from experiments. The modulation is modeled with three instances of type 401 in parallel and linear interpolation, as proposed by Hüsing and Pärisch (2020).

2.3 Photovoltaic - Thermal (PVT) collectors

An uncovered/WISC PVT collector with a finned air heat exchanger on the back side has been used in the investigation. The thermal parameters of the collector presented in Tab. 1 were determined by means of outdoor tests (Giovannetti et al. 2019) and validated for TRNSYS simulations (Chhugani et al. 2020). The electrical data of the PVT module is shown in Tab. 2. In the investigations, PVT Modules are facing south with tilt angle of 45 °.

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

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]
PV module	340	30	17.5	37.6	9.05	48.0	9.45	-0.39

In the bivalent heat source configurations, PVT is used solely if the PVT collector temperature is 5 K higher than BHE. Otherwise, only BHE is used as long as the BHE is available, because for the frost protection, inlet temperature of BHE has been restricted at -3 °C, after that only PVT is used until the bivalence point of heat pump is reached. On sunny days, BHE is regenerated with PVT heat, when the heat pump is not running and PVT temperature are higher than BHE. Once the BHE temperature reaches 25°C, regeneration is stopped and PVT heat is not used and rest produced heat from PVT is wasted.

2.4 Borehole heat exchanger (BHE)

The study investigates BHE as a single heat pump source or a combination with PVT. BHE and PVT are connected in parallel, and the higher temperature source is chosen 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, up to 150 m deep BHE was simulated. However, the length of BHE is under-dimensioned for multi-family houses (MFH) because the goal here is to investigate the possibility of BHE length reduction by integrating PVT collectors. TRNSYS Type 451 is used to model the BHE, which 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.

2.5 Air source heat pump

The air-source heat pump of the reference system has a thermal heating capacity of 14.9 kW and a COP of 3.65 at A2/W35, including defrosting losses. TRNSYS type 401 (Afjei and Wetter M. 1997) is also used for the air-source heat pump simulations with the built-in COP-reduction for defrosting. Additionally, 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 (Afjei and Wetter 1997). The COP reduction function of the simulated heat pump in this paper is derived according to experimental investigations from ISFH and presented for different relative humidity levels in (Chhugani et al. 2023). Moreover, as in a real system, de-icing with reverse operation can occur every 30 to 60 minutes on winter days. At that time, the heat pump can no longer supply energy to the building, which is to be compensated with a bigger storage volume and a higher thermal capacity. However, this intermittent operation cannot be simulated with type 401.

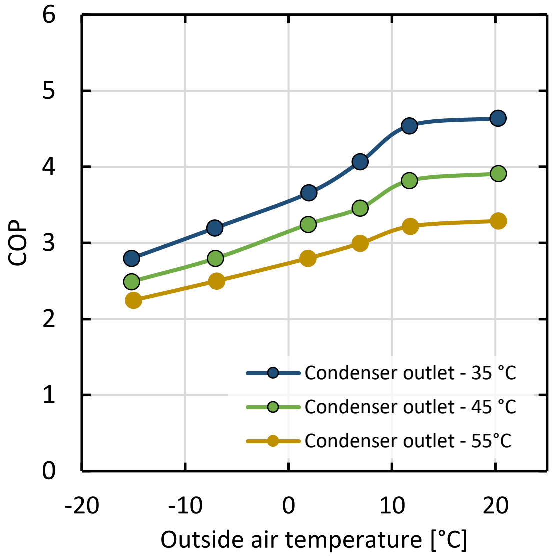

Fig. 4: Air source heat pump coefficient of performance for different air temperatures (x-axis) and condenser outlet temperatures (35 °C, 45 °C, 55 °C) with defrosting losses

2.6 Key performance indicators (KPIs)

The heat supply systems presented in the paper are evaluated and analysed based on two key performance indicators (KPIs). Firstly, the CO_2 emissions of the systems are calculated as the sum of the energy consumption values (electricity) and multiplied by the corresponding emission factors according to the German Building Energy Act (GEG) as shown in equation 1.

$$CO_{2,Emissions} = Final\ energy\ consumption\ (Electricity) \cdot x_{CO_2} \qquad \text{(eq. 1)}$$

Where the CO_2- emission factor (x_{CO_2}) of grid-taken electricity is 0.56 kg CO_2-equiv. for kWh, and self-consumed PVT/PV electricity is considered to have zero emission.

As second KPI, seasonal performance factors (SPF) are used to evaluate the system. The SPF_{bSt} (before storage) is the ratio of heat supplied to the buffer storage by the heat pump Q_{HP} and the auxiliary heating Q_{Backup} divided by the electrical energy consumed within this system boundary. $\dot{E}_{HP}$ is electrical energy of the heat pump compressor, $\dot{E}_{Pumps}$ is pumps energy and $\dot{E}_{Backup}$ is auxiliary heater electrical energy consumption. On the other hand, the $SPF_{bSt}^{(Grid)}$ describes the self-consumed PVT/PV electricity in the same system boundary. This means that the generated electrical power by PVT/PV is used simultaneously for the electrical consumption of the heating system (simulation time-step = 1 min), and the surplus PVT electricity is fed into the grid since there is no battery. Ultimately, this metric only considers the electrical energy drawn from the grid. Here, the household electricity profile is not covered in the consumption.

$$SPF_{bSt} = \frac{\int(\dot{Q}_{HP} + \dot{Q}_{Backup})\,dt}{\int(\dot{E}_{HP} + \dot{E}_{Backup} + \dot{E}_{Pumps})\,dt} \qquad \text{(eq.2)}$$

$$SPF_{bSt}^{(Grid)} = \frac{\int(\dot{Q}_{HP} + \dot{Q}_{Backup})\,dt}{\int_{>0}\left(\dot{E}_{HP} + \dot{E}_{Backup} + \dot{E}_{Pumps} - \dot{E}_{PVT/PV\ el\_Self}\right)dt} \qquad \text{(eq. 3)}$$

3. Results and discussion

Fig. 5 illustrates the seasonal performance factors (SPF) of the simulated systems. Here, simulation results are shown for combinations of different PVT areas (20 – 80 m²) with different BHE depths (1 - 150 m) as a heat source for the heat pump. Different colors in the graph show different ranges of $SPF_{bSt}^{(Grid)}$ for different PVT with BHE combinations, i.e., 60 m² PVT with BHE of 120 m, achieves $SPF_{bSt}^{(Grid)}$ of 3.46 (Range between 3.25 – 3.50). Similarly, the SPFs for further PVT - BHE combinations can be evaluated from Fig. 5.

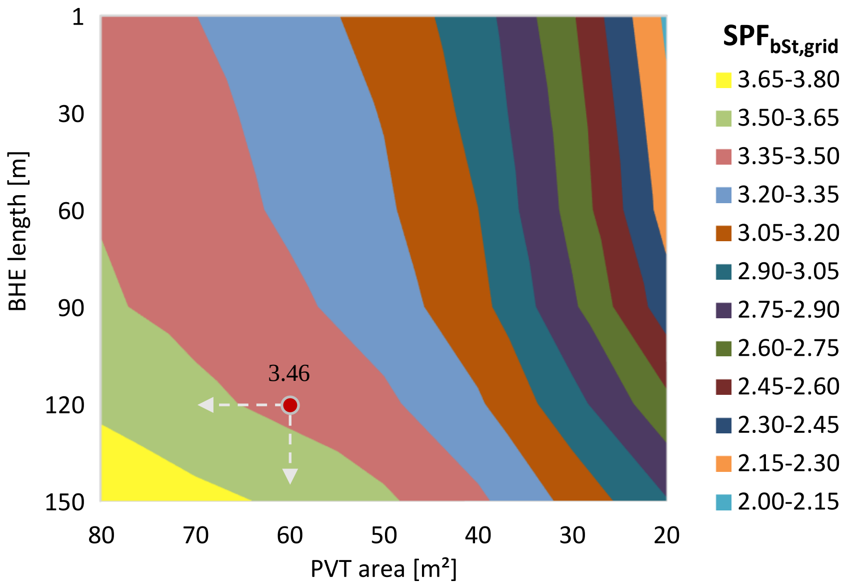

Fig. 5: SPF ranges of different PVT areas with BHE combination for heat pump systems, where the x-axis shows the PVT area and the y-axis indicates different borehole heat exchanger (BHE) lengths

Here, it is crucial to understand that the PVT combination with BHE opens the possibility of reducing BHE length without significantly affecting system efficiency. This aspect becomes economically more relevant for larger systems with two or more boreholes. On the other hand, ground regeneration via PVT heat generally ensures a sustainable system operation and can compensate for planning uncertainty even for small BHE installations.

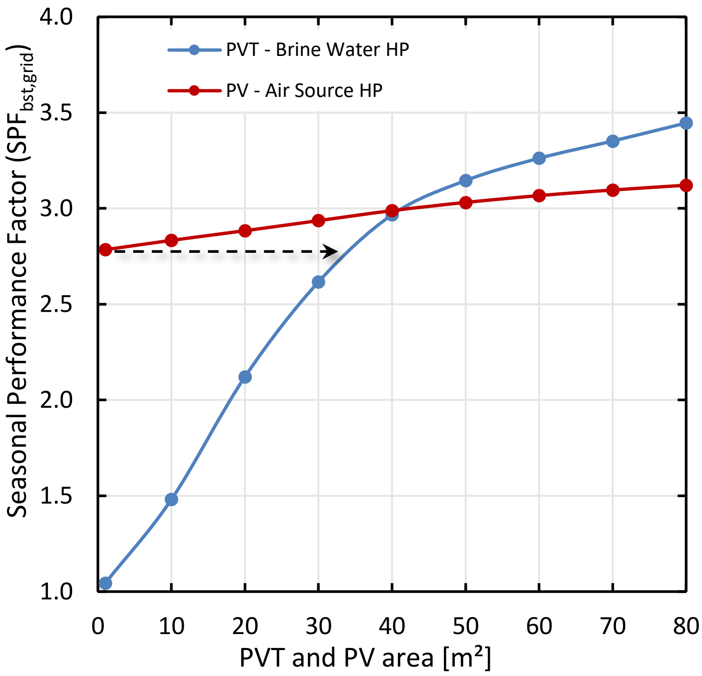

Fig. 6: SPF ranges of different PVT areas with brine-water heat pumps in comparison with different PV areas with air-source heat pump

Fig. 6 illustrates $SPF_{bSt}^{(Grid)}$ of the PV-assisted air-source heat pump and PVT with brine-water heat pump depending on the different PV or PVT areas. Here, the brine-water heat pumps use PVT as the only heat source. As Fig. 6 shows, the SPF rises gradually depending on the PVT collector area. With 80 m² PVT heat pump, the achieved SPF is 3.45, whereas the maximum accomplished SPF with 80 m² PV to air source heat pump is 3.12.

As indicated with black arrow in Fig. 6 that a minimum of ~35 m² PVT collector area is required for the brine-water heat pump source to reach similar SPF as PV with air-source heat pumps. With 40 m² PVT and PV area, both systems show similar efficiency, with larger areas PVT with brine-water heat pump system shows better performance than PV with air-source heat pump systems.

Fig. 7 shows the CO_2-equivalent of different simulated PVT - BHE combinations with heat pumps. As shown in the graph, the most efficient in terms of the lowest amount of CO_2 emissions (4.35 tons) is produced by 80 m² PVT and 150 m deep BHE with heat pumps. Small PVT areas of less than up to 20 m², combined with any BHE depths (here only up to 150 m deep), emit more CO_2 emissions than PV to air-source heat pumps. However, if a higher PVT area is added to the brine-water heat pump system (higher than 40m² PVT), then all the brine-water heat pump systems (only PVTs or combination of PVTs - BHE) are more efficient than PV to air-source heat pumps.

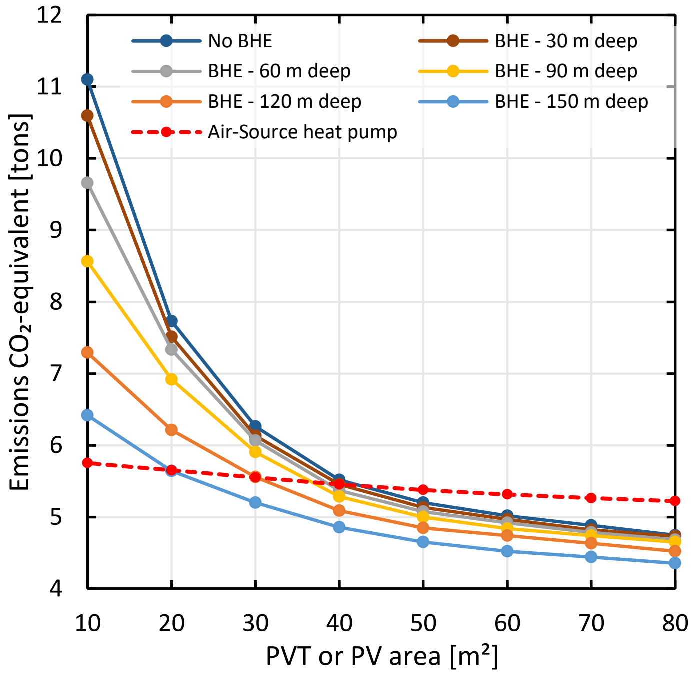

Fig. 7: CO_2-emissions for different PVT areas with BHE combination for heat pump systems for the multi-family house (MFH)

However, it can also be observed from the graph that the PVT combinations with smaller BHEs significantly reduce the CO_2 emissions, in some cases, such as only PVT (80 m²) with heat pumps can open the option to eliminate complete BHE without significantly emitting extra emissions.

4. Conclusion

The ongoing research project "integraTE" aims to comprehensively assess PVT with 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 these systems for the use in multi-family houses.

The following points summarize the essential findings of the simulations:

- PVT (80 m²) with borehole heat exchangers (BHE 150 m) to heat pump achieves a SPF of 3.76.
- PVT 35 m² collector area is required as the heat source for the brine-water heat pump to reach similar SPF as only air-source heat pumps.

- With PVT (80 m²) brine-water heat pump achieves SPF of 3.45, whereas PV (80 m²) to air source heat pump reaches maximum SPF of 3.12.

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 PV with air-source and geothermal heat pumps for the MFH. In the PVT-BHE configuration, PVT can favorably supply the heat to the heat pump directly or regenerate the ground source. As mentioned in the section 1, for the efficient heat pump operation with only borehole heat exchangers (BHE), three or four boreholes are required for multi-family houses. Integration of PVT plays here an important role, especially with larger installations like here in multi-family houses, where smaller dimensioning of BHE is possible. As presented in this paper that one BHE combination with PVTs can be very attractive and can be sufficient for efficient heat pump operation. Additionally, the solar regeneration via PVT enables a sustainable operation of the BHE field by avoiding long-term cooling effects.

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