Numerical study of the effect of hybrid solar collectors on the performances of the system combining PVT with heat pumps

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Abstract

Photovoltaic Thermal solar panels (PVT) are an interesting technology that converts solar energy into both electricity and heat in only one unit. This technology improves the conversion process efficiency of solar energy and optimizes the occupied area on the roof. PVT can be used as a heat source for heat pumps (H.P.), and the system can provide both space heating and domestic hot water efficiently and environmentally. Additionally, the electricity produced from PVT can be consumed directly by the heat pump system. The given paper presents a numerical study based on the characteristics of PVT and its effect on the system's performance. Transient simulations are performed with TRNSYS using a variable speed heat pump. Results show that, for the same number of installed PVT, the most influencing parameter is the first order heat losses coefficient (b_1) compared to the optical efficiency (η_0) of PVT, and system performance is improved when b_1 increases. For instance, with 20 PVT, the SPF is increased from 1,96 to 3,67 when the b_1 is increased from 5 to 35 (while the η_0 constant and equal to 50%). The numerical study presented herein is beneficial to design an efficient PVT dedicated to being coupled with heat pumps based on ratios combining costs and system performances.

Keywords: hybrid solar collectors (PVT), heat pump (H.P.), numerical simulations

1. Introduction

Hybrid solar panels, also known as Photovoltaic-Thermal collectors (PVT), supply heat and electricity simultaneously when exposed to sunlight. This technology improves solar energy conversion efficiency while optimizing the occupied area on the roof. Indeed, with similar dimensions to a photovoltaic panel, PVT can produce more than 2 times the total energy over the year. A real opportunity to use the produced energy of PVT efficiently all over the year is to combine them with brine/water heat pumps, as illustrated in figure 1. This attractive combination significantly improves the system performance by feeding the evaporator with the produced heat and covering part of the electrical consumption with the produced electricity. It allows using solar heat to provide space heating and domestic hot water for any residential building; however, buildings with higher heating demand require a more extensive PVT area.

Studying PVT-HP systems has attracted much attention during the last decade. Bai et al. (2012) have analyzed the performance of a PVT-HP system for sports center hot water production using TRNSYS. They showed that the achieved coefficient of performance is 4.11 in Hong Kong, with 66 % of the fraction of energy savings. In other cities in France, the obtained COP is more than 4.3, and the fraction of energy savings is more than 67%. Abu-Rumman et al. (2020) have established a PVT-Ground source heat pump (GSHP) system model using TRNSYS software to study the system performance enhancement. They showed that the average coefficient of performance of the HPs increased from 4.6 to 6.2 with a decrement of electricity consumption by more than 25%. In addition, they showed that such a system could reduce the photovoltaic panels' temperature by more than 20 °C, and improve the efficiency of electricity production by 9.5%. Chhugani et al. (2020) have investigated a system coupling unglazed liquid-based PVT collectors and heat pumps by means of yearly dynamic simulations in TRNSYS for space heating and domestic hot water. They showed that when PVT is used as a single heat source for heat pumps, the system efficiency is significantly increased and can be used as an alternative to an air source heat pump. Also achieved seasonal performance factors (SPF) are 3.18 and 3.49 (considering the electrical self-consumption of the HP) for the location of Zurich (Switzerland) with cold winters and warm summers. Del Amo et al. (2019) have analyzed the performance of a solar-assisted heat pump fed by PVT collectors using a validated TRNSYS model in Zaragoza (Spain). The obtained results show that the annual COP is 4.62 and that 67.6% of the PV yearly total production is directly consumed by the HP (37.8% of total electrical consumption of the HP).

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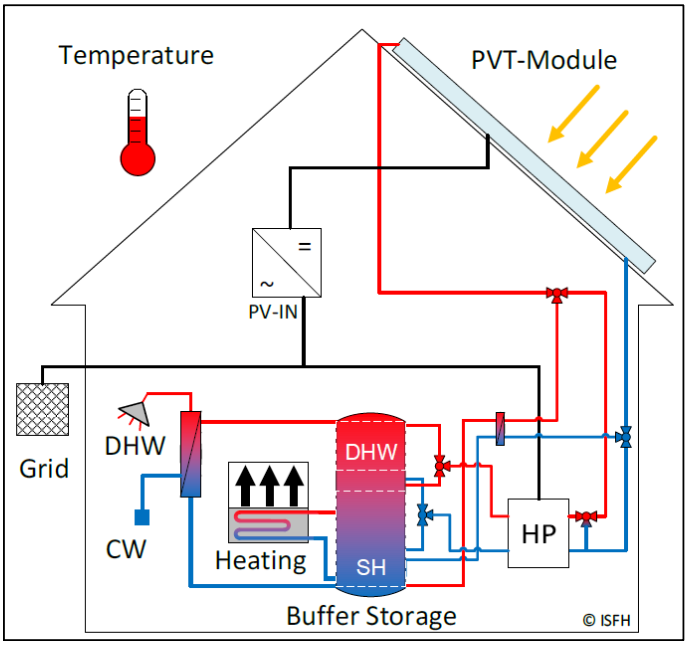

Fig. 1: System combining PVT modules with brine/water heat pumps

In order to reach the climate targets set by the European Commission for 2050, among other projects, the SunHorizon project, funded by the European Union's Horizon 2020 Research and Innovation Programme, has initiated in 2018. It aims to demonstrate the benefits in terms of GHG emissions and primary energy savings of the combination of PVT and HP for heating and cooling applications through eight European pilot sites (Chèze, 2021; Scotton et al., 2019). The main results show that more than 40% of GHG emissions and primary energy are saved compared to conventional systems. In a similar way, the « IntegraTE » European project, initiated in December 2019, aims to bring the PVT-HP system closer to the general public through five lighthouse projects. Main results show that PVT offers additional potential in addition to their capacity as an electricity source: they can provide HP with heat all year at a temperature level that improves system performances (Helmling et al., 2021).

However, many questions are still not answered about this system's design and sizing of PVT. This is the main reason behind the present study aiming to provide numerical results on the effect of the number and the characteristics of the used PVT on the performance of the PVT-HP system used for heating and domestic hot water needs. A variable speed HP is considered, and PVT are used alone to feed the evaporator directly with no intermediate tank. Simulations are carried out using the dynamic simulation software TRNSYS. In the following sections, the methodology used and the main assumptions are defined, and the obtained main results are discussed.

2. Methodology

The numerical simulations are performed using software TRNSYS v17.01.0028, where several models, so-called TRNSYS types were assembled to form and simulate the complete system. The PVT model for simulation (Type 203) was developed by the Institute of Solar Energy Research in Hamelin and validated for standard unglazed PVT collectors (Stegmann et al., 2011). The corresponding hydraulic diagram is shown in Fig. 2. PVT are used as a single heat source of the HP feeding directly the evaporator with no intermediate water tank. They are also connected to the bottom of the tank via an external exchanger. This loop is used for the PVT defrosting process; direct solar heating of the tank is not simulated here.

Simulations are performed for a single-family house SFH 45 located in Strasbourg (France) where the average outdoor temperature is 11 °C. The floor area of the building is 140 m^2 with a floor heating demand of approx. 42.5 kWh/(m^{2}a), with a one-minute weather data file from Meteonorm 8. Detailed building boundary conditions of this building are explained in (Dott et al., 2013). On the sink side, a hot water tank of 560 L is used for domestic hot water preparation and space heating.

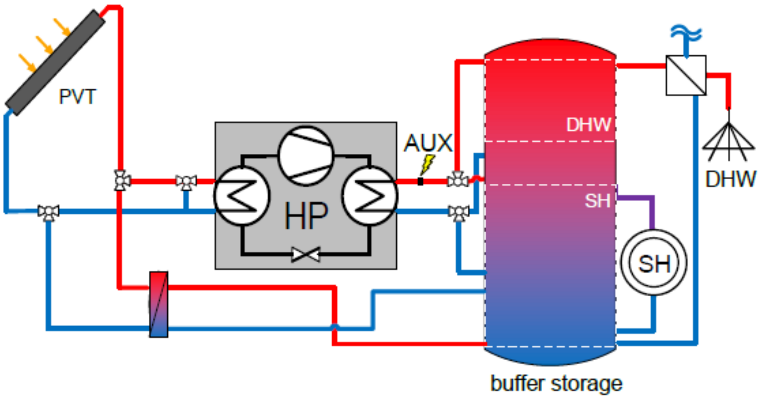

Fig. 2: Hydraulic diagram of the system with direct coupling system of PVT-HP

Fig. 2 shows the simulated PVT to heat pump configuration; the PVT collector works as the only heat source for the heat pump until the PVT outlet temperature falls below -12 °C. In the summer, if the PVT temperature is higher than the buffer storage tank, the heat pump is off then PVT heat is used directly to the storage tank. A brine-water inverter heat pump has been used with thermal power of 9.1 kW and a COP of 4.13 at B0/W35. **Erreur ! Source du renvoi introuvable.** shows the characteristic curve of the simulated variable speed heat pump.

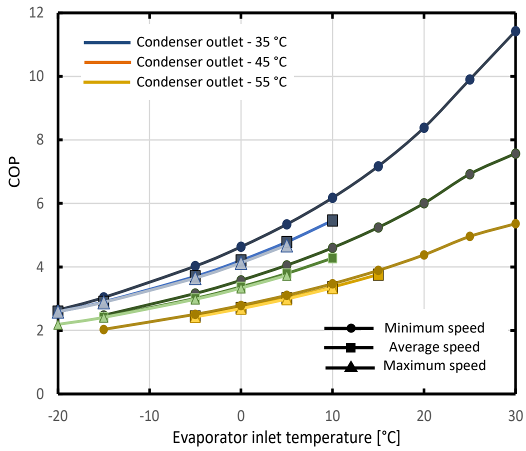

Fig. 3: Coefficient of performance (y-axis) for different evaporator inlet temperatures (x-axis) and condenser outlet temperatures (blue 35 °C, green 45 °C, yellow 55 °C) for three different compressor speeds

An electrical backup heater of 6 kW is used and located in the flow pipe of the heat pump. This heater takes over the charging of the storage tank when the temperature at the evaporator inlet at the heat pump drops below -12 °C. For the heat pump modelling, TRNSYS type 401 was used. A mixing valve is used at the evaporator inlet of the heat pump to protect from high temperatures coming from solar fields, and the maximum allowable temperature is 25 °C.

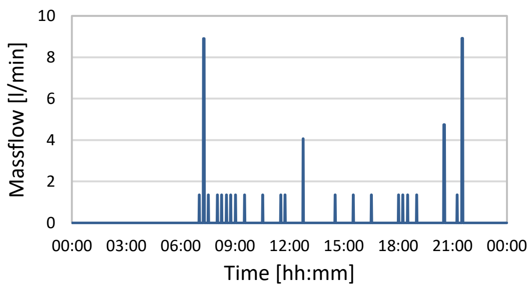

Fig. 4: Domestic hot water demand (DHW) of the building

The domestic hot water consumption is 145 L/d at 45 °C (2141 kWh/year), and water is tapped at 45 °C according to the daily DHW tap profile shown in Fig. 4.

In order to investigate and quantify the impact of PVT on system performance, different PVT collectors have been simulated and compared. The simulated collector parameters are presented below in Table 1. The unglazed PVT collector is liquid-based, with each module having 400 Wp of nominal power and 1.875 m^2 of area. In the PVT-heat pump systems, if the PVT collector temperature on cold days falls below the dew point of the air, then condensation (dew point > 0 °C) or frosting (dew point < 0 °C) occurs. The formation of frost reveals latent heat but inhibits the convection and irradiation gains. The required amount of heat for melting the frost depends furthermore on the PVT design. Now, there is no model to describe and simulate these effects accurately; however, defrosting is simulated as suggested in Chhugani et al. (2020) to reduce the uncertainty of TRNSYS type 203 for extreme conditions. Defrosting takes place when the following conditions meet, if the ambient air and dew point temperatures are below 0 °C, the heat pump is not running for at least 20 minutes, and still PVT collector temperature remains below -3 °C (frost point), then defrosting of PVT takes place and it stops once the temperature of the collector reaches 2 °C again.

Tab. 1: PVT characteristics

η_0 [-]: optical efficiency	0.35	0.35	0.5	0.5	0.5	0.65	0.65
b_1 [W/m^2.K]: first order heat losses coefficient	5	20	5	20	35	20	35
b2 [J/m³.K]: efficiency coefficient	0						
bu [s/m]: efficiency coefficient (in terms of wind)	0						
Number of PVT [-]	12 ; 20 ; 28						

3. Results

3.1. Simulations without defrosting

For each number of PVT (*N_PVT*), seven simulations are performed with different η_0 (optical efficiency) and b_1 (first order heat losses coefficient), whereas the efficiency coefficient b_2 and the efficiency coefficient (in terms of wind) *bu* are considered zero. Table 2 provides the obtained results for the case without defrosting. *Q_eva*, *Q_cond* and *Q_backup* stand for the annual thermal energy absorbed by the evaporator of the HP (which is produced by solar collectors), the thermal energy produced by the HP condenser (transferred to the water tank and then used for the house space heating and domestic hot water) and the produced thermal energy by the electrical heater, respectively. *E_HP* and *E_pump* stand for the annual electrical consumption of the heat pump (including the compressor and the evaporator pump) and the annual electrical consumption of the condenser pump, respectively.

Tab. 2: PVT-HP system results without defrosting

N_PVT [-]	η_0 [-]	b_1 [W/m^2.K]	Q_eva [kWh]	Q_cond [kWh]	E_HP [kWh]	E_pump [kWh]	Q_backup [kWh]	SPF [-]
12	0.35	5	3683	4922	1285	55.5	3652	1.61
12	0.35	20	5848	7832	2060	50.4	751	2.80
12	0.5	5	3598	4789	1236	56.2	3783	1.58
12	0.5	20	5786	7746	2033	50.4	833	2.75
12	0.5	35	6364	8461	2180	49.2	124	3.41
12	0.65	20	5770	7715	2019	50.4	862	2.74
12	0.65	35	6366	8461	2178	49.3	124	3.41
20	0.35	5	4622	6132	1567	53.0	2434	1.98
20	0.35	20	6386	8449	2145	49.3	142	3.43
20	0.5	5	4575	6049	1531	53.5	2511	1.96
20	0.5	20	6355	8406	2132	49.3	180	3.40
20	0.5	35	6538	8590	2136	49.0	0	3.67
20	0.65	20	6328	8360	2113	49.4	230	3.35
20	0.65	35	6537	8589	2136	49.0	0	3.67
28	0.35	5	5270	6966	1761	51.3	1587	2.36
28	0.35	20	6509	8554	2129	49.0	31	3.63
28	0.5	5	5114	6734	1683	51.8	1818	2.26
28	0.5	20	6505	8555	2132	49.0	31	3.62
28	0.5	35	6574	8590	2101	48.9	0	3.73
28	0.65	20	6507	8546	2121	49.1	46	3.62
28	0.65	35	6575	8593	2102	49.0	0	3.73

For the evaluation of the system performance, the SPF_{SHP} is considered according to IEA Task - 44 SHP boundary conditions and explained in Malenković et al. (2012), which is the ratio between the annual heat delivered by the system (for space heating and domestic hot water) and the electrical energy consumed by the system (the compressor, evaporator and condenser pumps, the electrical heater and the defrosting pump). The formula is given by the following equation:

$$SPF = \frac{\int(\dot{Q}_{SH}+\dot{Q}_{DHW})dt}{\int(\dot{E}_{HP}+\dot{E}_{pump}+\dot{E}_{backup}+\dot{E}_{defrosting})} \quad \text{(eq. 1)}$$

It is worth noting here that the consumed PVT electricity directly by the heating system is not subtracted from the electrical consumption of the system. Only the thermal performance is calculated here, even if it is well known that this self-consumption of PVT electricity could enhance the system's performance.

Figures 5 to 7 illustrate the results obtained by variation of PVT panels 12, 20 and 28. *E_system* stands for the electrical energy consumed by the whole system. For all simulations, the system covers both space heating and domestic hot water demands; when the HP reaches its operation limits, the electrical heater takes over the charging of the storage tank.

When figures 5 to 7 are compared, the results show that no matter the PVT characteristics; η_0 (optical efficiency) and b_1 (first order heat losses coefficient), the system performance is enhanced when the number of PVT panels increases: the total heat absorbed by the evaporator increases and the total electrical energy consumed by the system decreases. This is normal and expected; however, this has a significant impact on solar installation. It requires a higher initial cost for the additional PVTs, and more roof area for these PVTs to be installed. Moreover, the effect of the increased number of PVT is more significant for the least efficient PVT. This effect is less noticeable for the PVT with higher characteristics. This can also be explained by the limited heat consumption of the house.

When the obtained results of each figure (the same number of PVT) are compared, one common thing that can be presumed is that the system performance is highly influenced by $b_{1,}$ and the $\eta 0$ has almost no effect on the solar produced heat and the consumed electricity of the whole system. This means that PVT is not required to be efficient in converting solar radiations into heat (high optical efficiency η0), but it should work as an environmental heat exchanger with a higher heat loss coefficient (b_1). There are several reasons behind this; firstly, the PVT operation temperature is often less than the ambient temperature during colder winter days or at night; hence, high heat exchange to the ambient air is very beneficial. The calculated average temperature during the running time in PVT for all performed simulations is about -0,61 °C. Secondly, the heat demand is higher during cold winters so that during periods in which the solar radiations are very low or null, an optically performant PVT would behave in the same manner as a non-performant one. The third specific reason is the hydraulic system configuration: the direct heating of the water tank by PVT is not considered, and no buffer storage tank between the PVT and the evaporator of the HP is integrated.

Moreover, it is noticed that the system performance enhancement is more significant between the smallest and the moderated heat loss coefficients (from b1: 5 to b1: 20 W/m²K) than between the moderated and the largest ones (from b1: 20 to b1: 35 W/m²K). This means that a moderated heat loss coefficient (here b1: 20 W/m²K) is sufficient for a PVT – heat pump operation. The moderated heat loss coefficient can be obtained by choosing a very conductive material and by improving the design of the heat exchanger on the back side PVT by adding fins, for instance. These could lead to significantly higher costs for one PVT. We believe these results are more beneficial when converted into ratios considering the manufacturing cost of one PVT.

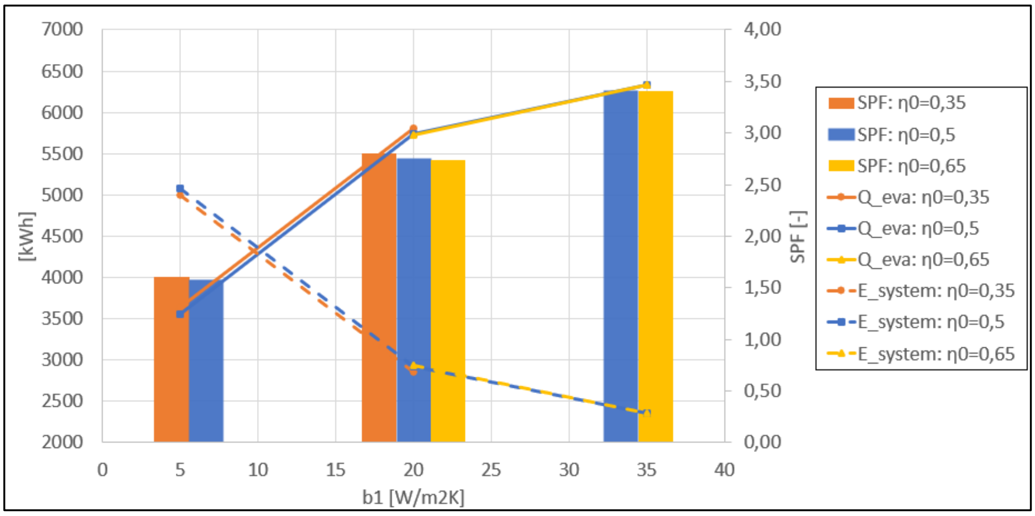

Fig. 5: Simulation results with 12 PVT

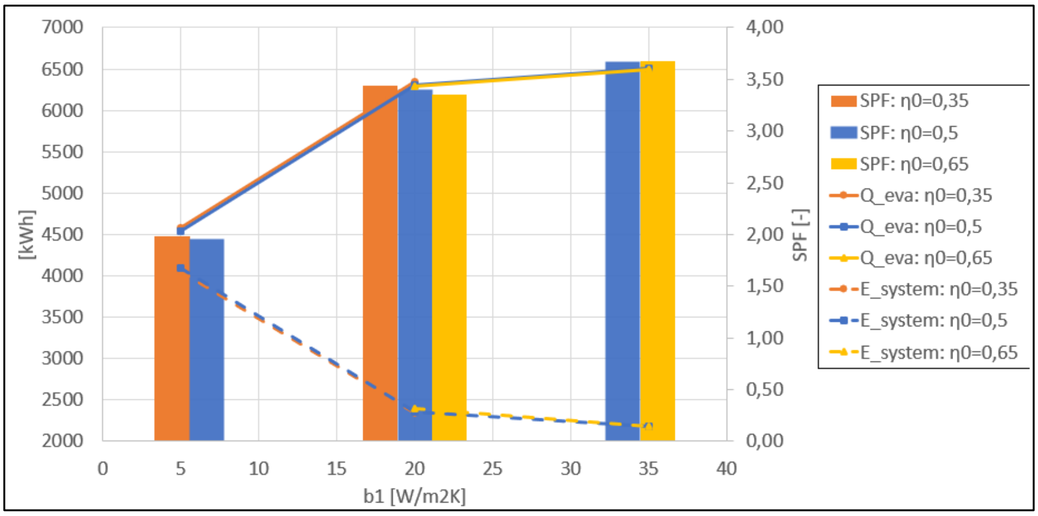

Fig. 6: Simulation results with 20 PVT

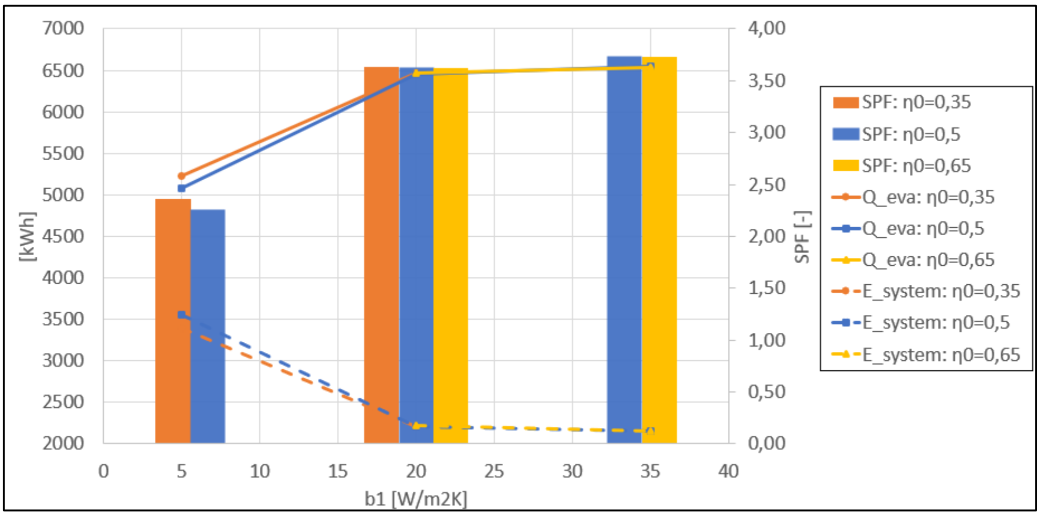

***Fig. 7:* Simulation results with 28 PVT**

3.2. Simulations with defrosting

This sub-section provides the numerical results with defrosting process considered (table 3). When compared to the results of table 2 (without defrosting), it is commonly seen that for the same case (same number and characteristics of PVT), the seasonal performance factor of the system with defrosting is slightly lower than the system without defrosting. In some cases (the first one in the tables, for instance), in which the energy consumed by the electrical heater is lower with defrosting, the results show that the energy needed to defrost the PVT is higher than the difference between the needed energy consumed by the backup to take over the heating of the water tank. For other cases (the cases with 20 PVT and optical efficiency of 0.5, for instance), it is seen that even if the PVT is defrosted, the electric heater can consume more energy than the cases without defrosting deteriorating the system seasonal performance (the difference is noticeable more with lower b_1 (5 W/m²K) than the moderate/higher b_1). It proves that for the same η_0 (here is 0.5), higher heat loss coefficients play an essential role in efficient PVT – HP operation and can make a very robust system.

Tab. 3: PVT-HP system results with defrosting

N_PVT [-]	η_0 [-]	b_1 [W/m^2.K]	Q_eva [kWh]	Q_cond [kWh]	E_HP [kWh]	E_pump [kWh]	Q_backup [kWh]	Q_defrost [kWh]	SPF [-]
12	0.35	5	3900	5213	1361	58.4	3783	-420.19	1.54
12	0.35	20	5960	7981	2098	51.6	806	-208.47	2.71
12	0.5	5	3779	5018	1286	58.5	3971	-417.12	1.51
12	0.5	20	5902	7894	2068	51.7	902	-215.37	2.65
12	0.5	35	6442	8565	2207	50.1	159	-139.51	3.31
12	0.65	20	5924	7923	2074	51.9	886	-229.98	2.66
12	0.65	35	6432	8552	2203	50.1	168	-134.18	3.31
20	0.35	5	4871	6458	1648	55.8	2572	-463.30	1.87
20	0.35	20	6472	8563	2173	50.3	200	-174.43	3.30
20	0.5	5	4740	6254	1573	56.4	2800	-485.55	1.81
20	0.5	20	6469	8556	2169	50.5	232	-198.30	3.27
20	0.5	35	6647	8737	2176	49.9	0	-145.73	3.60
20	0.65	20	6456	8536	2162	50.7	262	-211.07	3.23
20	0.65	35	6647	8738	2177	49.9	0	-149.37	3.59
28	0.35	5	5375	7081	1773	54.4	1935	-452.73	2.12
28	0.35	20	6644	8739	2180	50.1	29	-178.38	3.54
28	0.5	5	5209	6832	1688	55.0	2197	-466.12	2.03
28	0.5	20	6653	8753	2183	50.2	31	-193.79	3.53
28	0.5	35	6689	8747	2145	49.9	0	-156.17	3.64
28	0.65	20	6663	8755	2176	50.4	56	-220.11	3.50
28	0.65	35	6688	8751	2149	49.9	0	-161.95	3.64

As mentioned before, the reason for implementing defrosting in simulations is that frost is a very common phenomenon with PVT-heat pump operation, as explained in Chhugani et al. (2020). The ice formation on the collector field hinders the heat transport from the ambient to the collector, and this occurs when PVT operates under extreme conditions (heat pump running continuously, no direct sunshine for many days), which can be reduced by higher heat loss coefficient. It is also worth mentioning that the defrosting phenomenon requires the installation of an extra hydraulic circuit with a heat exchanger and a pump. In addition, the water tank needs to be upgraded with one extra heat exchanger. All of these have an extra cost to be added to the system.

4. Conclusion

The present paper focuses on the energy system combining hybrid solar panels (PVT) and heat pumps (HP) to provide both space heating and domestic hot water needs. It presents a numerical study investigating the effect of PVT characteristics and numbers on the system's performance. Transient simulations are performed using TRNSYS for a single-family house located in Strasbourg (France).

The obtained results showed that the PVT characteristics and number are crucial on the system annual performances which vary between 1.5 and 3.7. They also showed that no matter the PVT characteristics; η_0 (optical efficiency) and b_1 (first order heat losses coefficient), the system performance is enhanced when the number of PVT panels increases. however, this has a significant impact on solar installation cost. When the same number of PVT is considered, the system performance is shown to be highly influenced by b_1, and the η0 has almost no effect on the solar produced heat and the consumed electricity of the whole system. Therefore the involved PVT is not required to be efficient in converting solar radiations into heat (high η_0), but it should work as an environmental heat exchanger with a higher heat loss coefficient (b_1).

Simulations with PVT defrosting process considered showed that the system performance is detorierated compared with simulations without defrosting. This is explained by the extra consumed thermal energy by the system to defrost PVT. However, these results are more realistic since the implemented model, like others, is not able to correctly simulate the variation of the convective heat transfer coefficient of the PVT with the air when frost is produced which is still a very complex topic. The energy needed to defrost PVT compensates losses in the convective heat coefficient of the PVT.

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