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PYTHON-BASED DYNAMIC SIMULATION OF A PVT-HEAT PUMP SYSTEM: OPERATING-MODE ANALYSIS AND COMPARISON WITH AN AIR-SOURCE HEAT PUMP

Summary

A fully-Python dynamic simulation model of an indirect-expansion PVT solar-assisted heat pump (IDX-PVT-SAHP) is presented, in which unglazed Wind- and Infrared-Sensitive (WISC) PVT collectors are the sole heat source of a brine/water heat pump. The cold-source temperature pinch is analysed by operating mode (daytime/night-time, space heating/DHW), revealing a positive pinch during the day and a negative one at night due to long-wave radiative losses. The system is benchmarked against an air-source heat pump (ASHP) with a fully disclosed manufacturer performance map and four defrosting-penalty scenarios. At the reference climate (Strasbourg, SFH45), the IDX-PVT-SAHP achieves $SPF_{SHP} = 3.1$ and outperforms the ASHP as soon as a moderate defrosting penalty is applied. The results highlight the critical role of the frosting/defrosting model in any such comparison, and the need for transparent field-measured performance data for both system types.

Keywords: photovoltaic-thermal collector, solar-assisted heat pump, indirect expansion, WISC, seasonal performance factor, frosting

Field of application: Solar heating, heat pump systems, residential building energy renovation

Addressed audience: Solar thermal and heat pump researchers, building energy engineers

1. Introduction

With the urgent need to reduce greenhouse gas emissions, space heating and domestic hot water (DHW) for buildings – which account for around 15% of the European Union's total emissions (European Commission, 2020) – must increasingly rely on heat pumps. The most common and cost-effective solution is the Air-Source Heat Pump (ASHP) system. A conceptually straightforward evolution consists in replacing its compact outdoor unit with a roof-mounted field of solar collectors that harvest heat from both ambient air and solar radiation (Kramer et al., 2023; Miglioli et al., 2023). Liquid-based photovoltaic-thermal (PVT) collectors can be both the sole heat source of the heat pump and electricity generators offsetting the compressor demand in a *single-source indirect-expansion PVT solar-assisted heat pump* (IDX-PVT-SAHP) system.

To operate efficiently at night on ambient heat alone, such collectors must be unglazed – designated Wind- and Infrared-Sensitive Collectors (WISC).

The system operates in contrasting regimes. At night, the collector field acts as a large air-to-brine heat exchanger. During the day, solar irradiation raises the evaporator inlet temperature – improving the COP – or enable passive frost melting. Whether the IDX-PVT-SAHP outperforms the ASHP over a heating season depends on the balance between these two modes, and therefore on climate, collector characteristics, panel area, building demand, and system configuration.

Despite growing interest, the literature presents systematic gaps. No fully transparent and reproducible simulation model exists: published studies rely on proprietary platforms (TRNSYS, Polysun) with limited component-level disclosure. Results are confined to global annual metrics or monthly-averaged temperatures, without disaggregation by operating mode (Jaafar et al., 2022; Nielsen et al., 2024). Moreover, Chhugani et al. (2023) include a parallel summer mode in which PVT heat feeds directly into the DHW tank, use a partially disclosed heat pump performance map, and apply a single defrosting-penalty assumption – all of which limit the generalisability of their ASHP comparison. Importantly, no study has yet demonstrated a clear seasonal performance advantage of properly sized and installed IDX-PVT-SAHP over ASHP system serving the same building — a gap explicitly noted by Kramer et al. (2023).

This paper takes a first step toward filling these gaps through: (i) a fully-Python dynamic model following the architecture of TRNSYS Type 1286 (PVT) and Type 402 (heat pump), enabling reproducible simulation; (ii) a disaggregated operating-mode analysis (daytime/night-time, space heating/DHW); and (iii) an ASHP comparison with a fully disclosed manufacturer performance map and four explicit defrosting-penalty scenarios.

2. Methodology

2.1 System description

The system comprises: (a) a field of liquid-based WISC PVT collectors in a glycol/water primary loop which is the sole heat source of (b) a brine/water heat pump; (c) a hydronic space heating (SH) circuit with dynamic radiator model (EN 442); (d) a domestic hot water (DHW) tank supplied exclusively by the heat pump condenser; and (e) a building thermal model. Since brine/water heat pumps must have evaporator inlet temperature lower than a limit (typically 25°C), there is a thermostatic valve at the outlet of the solar panels. PV electricity self-consumption offsets compressor demand when simultaneous. The system is illustrated in Fig. 1.

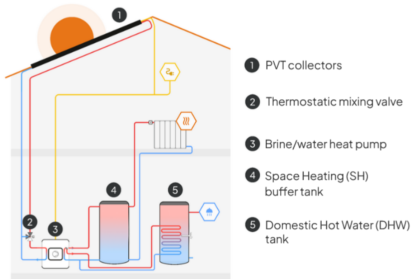

Fig. 1: Schematic of the IDX-PVT-SAHP system with an additional space heating buffer tank. In the present study, the heat pump condenser is directly connected to the hydronic heating circuit.

2.2 Simulation model

The model is implemented entirely in Python. The PVT collector follows the quasi-dynamic thermal output formulation of ISO 9806 (ISO, 2025). This component mirrors the structure of TRNSYS Type 1286 (TESS, 2023), validated against experimental data in prior work. The heat pump follows the TRNSYS Type 402 (Transsolar, 2012) architecture: condenser power and compressor consumption are interpolated (polynomial or RBF) from a fully disclosed manufacturer dataset as functions of evaporator inlet and condenser outlet temperatures and compressor speed. The building is modelled as a single thermal capacitance (like TRNSYS Type 88) driven by hourly TMY data from PVGIS. The coupled system is solved at a 5-minute time step via fixed-point iteration; a full annual simulation completes in about 5 to 10 min on a standard laptop.

2.3 Simulation setup

The reference building is a renovated single-family house (SFH45 from IEA SHC Task 44, Dott et al. 2013) located in Strasbourg. The PVT field consists of 14 Dualsun SPRING MAX panels[1] (Dualsun, 2024). The brine/water heat pump is the Ecoforest ecoGEO$^+$ 1-9 (EcoForest, 2024b) and the air/water reference is the EcoForest ecoAIR$^+$ 1-9 Pro (EcoForest, 2024a). PVT panels are assumed to require no defrost cycle, as supported by experimental evidence (Leibfried et al., 2018). For the ASHP, defrosting is modelled as a COP reduction that depends on outdoor temperature and relative humidity, using the experimental penalty curve of Chhugani et al. (2023) (their Fig. 3b, measured at ISFH). Although this curve was not derived for the specific ecoAIR$^+$ model used here, it is the most complete experimentally grounded dataset available in the literature; we therefore adopt it as a *reference penalty* and assess sensitivity through four scenarios: (A) no penalty; (B) 0.5× the reference penalty; (C) the reference penalty; and (D) 1.2× the reference penalty.

[1] *SPRING4 425 TOPCon Finned*

3. Preliminary results

3.1 Operating-mode temperature pinch

Fig. 2 shows the pinch between evaporator inlet and outdoor ambient temperatures $\Delta T_{\text{pinch}} = T_{\text{HP,Eva,in}} - T_{\text{amb}}$ as a function of outdoor temperature, disaggregated by daytime and night-time operation. At night, the pinch is around -4 K and becomes more pronounced at lower outdoor temperatures, where skies are typically clearer and radiative losses larger. During the day, absorbed solar irradiation yields a higher pinch than during the night (by $\approx$ 1 K on average over HP operation) – improving the COP. In the complete results, the pinch curve and the COP curve are plotted separately for night and day for each service (space heating and domestic hot water production) for both the IDX-PVT-SAHP and ASHP systems.

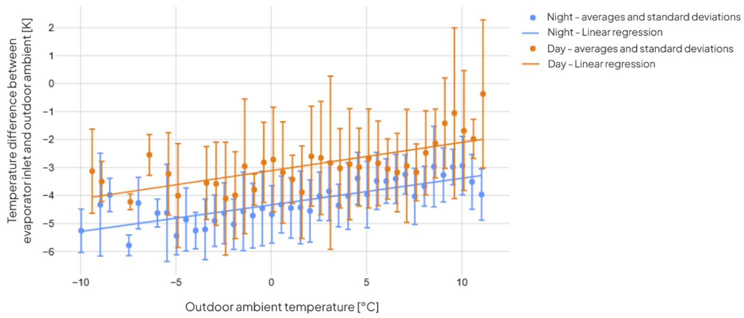

Fig. 2: Evaporator inlet temperature pinch ($T_{\text{HP,Eva,in}} - T_{\text{amb}}$) vs. outdoor temperature, separated by daytime and night-time operation. IDX-PVT-SAHP providing space heating and DHW for a SFH45 in Strasbourg.

3.2 Comparison with the air-source heat pump

Tab. 1 benchmarks the two systems under the four defrosting scenarios. Without defrosting penalty (scenario A), the ASHP achieves a higher SPF than the IDX-PVT-SAHP (+5.8%), confirming that night-time operation is a genuine disadvantage for the PVT field as a heat source. However, even a moderate defrosting penalty (scenario B, half the *reference*) nearly closes the gap (−0.6%), and with the *reference penalty* (scenario C) the IDX-PVT-SAHP is already 7.4% better in performance factor.

Tab. 1: Seasonal performance factor SPF_{SHP} calculated based on Malenkovic et al. (2013) – IDX-PVT-SAHP vs. ASHP under four frosting scenarios. Reference: Strasbourg, SFH45 (space heating demand of $\approx$ 46 kWh/m^2/y and DHW demand of $\approx$ 2100 kWh/y).

System	Frosting scenario	SPF_{SHP}	ΔSPF vs. ASHP
IDX-PVT-SAHP	(–) No frosting applicable	3.10	—
ASHP + PV	(A) No penalty	3.28	−5.8%
ASHP + PV	(B) Half measured penalty	3.08	+0.6%
ASHP + PV	(C) Measured penalty	2.87	+7.4%
ASHP + PV	(D) 1.2× measured	2.78	+10.3%

4. Conclusions

A transparent, fully-Python dynamic model for IDX-PVT-SAHP systems has been applied to a single-family house in Strasbourg. Disaggregated analysis reveals a higher daytime average pinch by about 1 K that improves COP, contrasted with less efficient operation at night compared to an ASHP system, if one does not take into account its frosting/defrosting cycles. Comparison with an ASHP shows that the IDX-PVT-SAHP ($\text{SPF}_{\text{SHP}} = 3.1$) outperforms as soon as a moderate defrosting penalty is applied. The result highlights the critical importance of transparent, climate-specific defrosting models in any PVT-SAHP vs. ASHP comparison. Future work should extend the analysis to further climates and configurations, but also — and critically — address the lack of reliable field-measured ASHP and IDX-PVT-SAHP performance data for the same heat demand, including real frosting/defrosting cycles across diverse conditions. It is also acknowledged that PVT panels may occasionally require defrosting to prevent thick ice slab formation — a safety concern not captured by the present model.

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