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Dynamic Assessment of a PVT-GSHP System for Demand-Side Decarbonisation in Residential Buildings#

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ABSTRACT

Decarbonisation of heat in residential buildings remains a critical challenge in achieving net-zero energy goals. This paper presents a dynamic simulation and performance evaluation of a hybrid energy system integrating photovoltaic-thermal (PVT) solar collectors with a ground-source heat pump (GSHP) to meet the space heating demand of a terraced house. The system was modelled using TRNSYS, enabling detailed hourly performance analysis under varying weather and load conditions. Borehole heat exchangers, thermal energy storage and the control logic are explicitly modelled to reflect realistic operational behaviour. Results show the system's ability to deliver demand-side flexibility, reduce grid dependency and enhance seasonal performance. The coupled PVT-GSHP system achieves a stable coefficient of performance while maintaining acceptable indoor thermal comfort. This study contributes to the growing evidence supporting hybrid low-carbon technologies for residential heating solutions.

Keywords: renewable energy resources, ground-source heat pump, photovoltaic thermal systems, demand-side flexibility, dynamic modelling, TRNSYS

NOMENCLATURE

Abbreviations	
COP	Coefficient of performance
DST	Duct ground heat storage
GSHP	Ground-source heat pump
PV	Photovoltaic
PVT	Photovoltaic thermal
TMY	Typical meteorological year
UK	United Kingdom
Symbols	
A_c	Collector area [m^2]
F_R	Heat removal factor [-]
G_T	Total incident solar radiation [W/m^2]
P_e	Electrical output [W]
Q_{th}	Thermal energy gain [J]
T_a	Ambient temperature [°C]
T_c	Average PV cell temperature [°C]
T_{fi}	Fluid inlet temperature [°C]
T_{ref}	Reference cell temperature [°C]
U_L	Overall heat loss [W/(m^{2}K)]
α	Absorptance [-]
β	Temperature coefficient [1/°C]
τ	Transmittance [-]
η_{ref}	Reference electrical efficiency [-]

1. INTRODUCTION

Decarbonisation of the residential heating sector represents a major barrier in the global transition towards net-zero energy systems. In the United Kingdom (UK), space heating and domestic hot water account for over 60% of household energy consumption [1], with building operations contributing approximately 30% of global energy use and a quarter of CO_2 emissions [2]. Achieving UK's legally binding 2050 net-zero target and global climate goals requires widespread adoption of low-carbon technologies in homes [3].

Ground-source heat pumps (GSHPs) have emerged as a promising solution to replace fossil fuel-based boilers in temperate regions. By leveraging the stable subsurface temperature, GSHPs can deliver high efficiency heat with minimal on-site emissions [4]. Compared to air-source heat pumps, GSHPs offer greater operational stability across seasons and are well-suited for integration with high-performance building envelopes [5]. However, the long-term thermal imbalance resulting from disproportionate ground heat extraction can degrade performance and threaten system sustainability [6,7].

To mitigate this issue, hybrid renewable energy systems incorporating photovoltaic-thermal (PVT) collectors have been proposed [8]. PVT systems

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simultaneously generate electricity and capture low-grade heat, which can be injected into the ground loop during periods of surplus solar radiation. This dual function supports borehole heat regeneration, reduces reliance on auxiliary electricity and aligns with demand-side management strategies [9]. Additionally, such configurations improve system autonomy and offer resilience in decentralised energy settings [10].

Recent studies using dynamic simulation platforms have highlighted the operational potential of PVT-GSHP systems. In [11], a hybrid configuration model for a hot climate was presented, with significant improvements in seasonal performance being reported. Similarly, it was shown in [12] that solar-assisted GSHPs may achieve favourable energy and economic outcomes over a 20-year horizon if deployed in moderately cold climates.

While previous studies have shown the feasibility of integrated PVT-coupled GSHP systems using dynamic simulations, they have typically focussed on long-term, idealised conditions or multi-dwelling/community-scale applications. Few works have examined short-term, seasonal performance under realistic control strategies, particularly in UK-based single-family homes. Moreover, the role of PVT-driven borehole regeneration during the winter heating season, when solar availability is limited but thermal demand peaks, remains underexplored.

This paper addresses the limitations just described by developing a dynamic simulation-based assessment of a PVT-coupled GSHP system tailored for a typical residential building in South Wales, UK. The integrated PVT-GSHP system, shown in Fig. 1, was modelled in TRNSYS. Unlike previous studies, it incorporates realistic weather data for the winter season alongside component-level control (including heat exchanger coupling between the PVT and borehole loops).

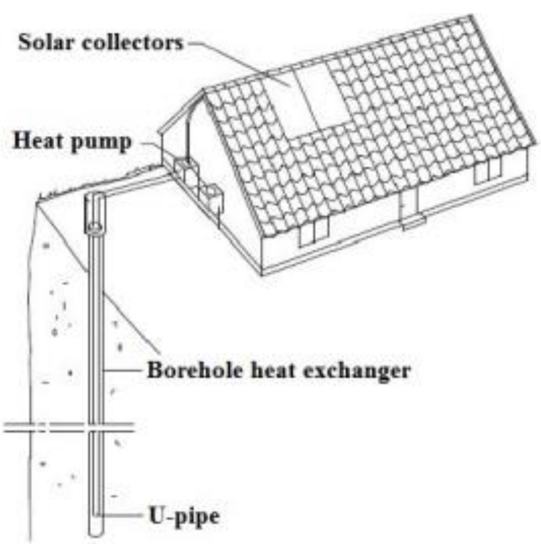

Fig. 1. Dwelling with PVT-integrated GSHP system [13].

The model of the dwelling was verified against published benchmark data from the literature for a comparable residential building, enhancing confidence in the methodology and simulation outcomes. The verified modelling framework was then used to explore the behaviour and operational potential of the integrated PVT-GSHP system. An assessment of the thermal energy demand, coefficient of performance (COP) dynamics and PVT thermal/electrical performance of the system under UK-specific conditions was carried out. Through the adopted approach, the paper offers practical insights to support low-carbon retrofitting strategies and the scalable deployment of hybrid renewable heating solutions in residential settings.

2. METHODOLOGY

2.1 *Building Description*

The system under investigation was designed to meet the heat demand of a typical three-bedroom terraced house located in Neath-Port Talbot, Wales, UK. A schematic of the house is shown in Fig. 2. The building has a total conditioned floor area of 79 m² and an approximate internal volume of 180 m³. Thermal loads for space heating were calculated based on standard occupancy profiles and internal gains derived from the CIBSE guidelines [14], ensuring realistic representation of residential energy usage patterns.

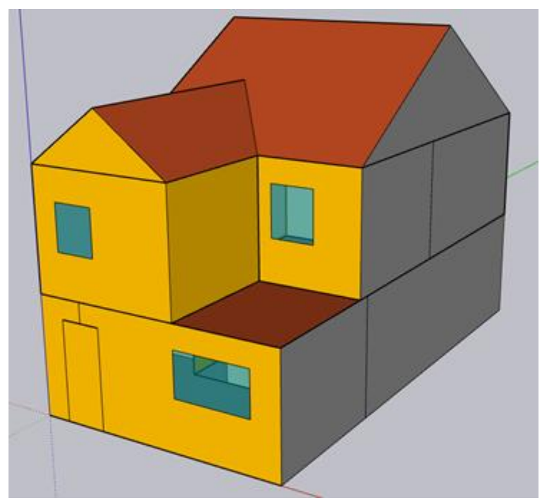

Fig. 2. Schematic of the investigated three-bedroom terraced house (developed using SketchUp).

2.2 *Hybrid PVT-GSHP System Configuration*

The hybrid system, shown in Fig. 3, integrates a roof-mounted PVT solar collector with a vertical GSHP to form a hybrid low-carbon heating solution. The system layout was designed to maximise the synergistic use of solar and geothermal energy while improving year-round performance through ground thermal recharge.

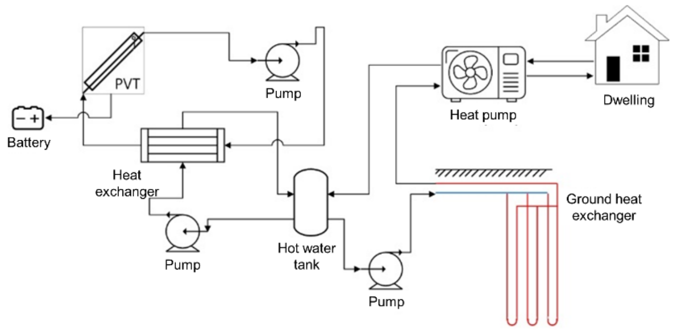

Fig. 3. System schematic.

The PVT subsystem consists of a liquid-based flat-plate collector with a surface area of 4.18 m² and electrical and thermal efficiencies of 14% and 51%. It is oriented to maximise solar gain and serves a dual function: producing electricity and injecting surplus thermal energy into the ground loop during periods of high solar availability.

The GSHP subsystem considers a vertical U-tube borehole heat exchanger charged with a water-antifreeze mixture as heat transfer fluid. The ground thermal conductivity and volumetric heat capacity are assumed as 4.68 kJ/(hr·m·K) and 2,016 kJ/(m³K), which are representative of local geological conditions. The ground loop circulates fluid through the borehole field, enabling heat extraction in winter and heat rejection during summer. Energy exchange between the heat pump, borehole loop and the building is managed via a buffer tank and a set of internal heat exchangers.

In this configuration, the PVT panels serve primarily as a ground regeneration mechanism, helping offset the long-term thermal imbalance commonly associated with GSHP systems operating in heating-dominated climates [15]. This thermal recharge strategy supports sustained ground temperature stability, leading to enhanced seasonal performance of the heat pump. The integration of solar and geothermal technologies into a single hybrid system also facilitates reduced reliance on external electricity supply, promoting a low-carbon, high-efficiency energy solution for residential buildings.

3. NUMERICAL MODELLING APPROACH

A dynamic model of the PVT-coupled GSHP system was developed using TRNSYS, a modular simulation environment for transient thermal system analysis. The high-level system configuration is shown in Fig. 4. This includes the thermal subsystems and main control loops.

This section outlines the simulation setup, control logic and underlying mathematical models of the key components of the PVT-GSHP system.

3.1 *TRNSYS Simulation Setup*

The simulation was configured with a time step of 0.5 minutes to capture short-term fluctuations and control interactions over the simulated period. The model was created using the TRNSYS Type list shown in Table 1.

Weather inputs were based on an EnergyPlus file. This enabled location-specific solar radiation and ambient temperature profiles for Neath-Port Talbot.

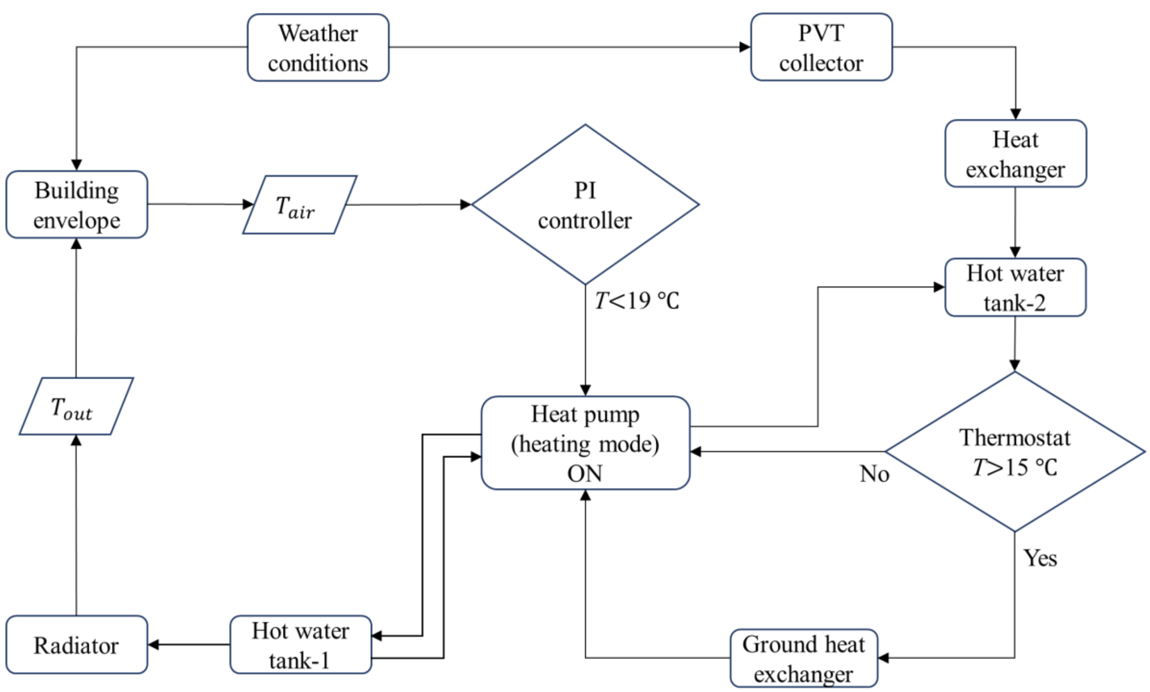

Fig. 4. Block diagram of the PVT-GSHP system showing component interactions.

Table 1. TRNSYS types used in system modelling.

Components	Type
Weather data reader	15–3
Building	56
Controllers	23
PVT	50c
Thermal Storage	158
Water-to-water heat pump	9271
Borehole	548a
Heat exchanger	91
Flows pumps	114
Diverter, mixers	11f, 11h
Outputs	65c, 65d

3.2 Control Strategy

System operation is governed by a set of temperature-dependent and proportional-integral (PI) control loops. Operation of the heat pump is managed by an independent PI controller to maintain target setpoints for indoor thermal comfort. During periods of high solar irradiance, the PVT collector contributes excess thermal energy to the ground loop, governed by a temperature-based control algorithm that ensures ground regeneration. This control logic prevents long-term thermal depletion of the ground reservoir and enhances the overall seasonal performance of the system.

3.3 Mathematical Modelling of System Components

The key governing equations for thermal and electrical performance of TRNSYS components are taken from [16, 17] and summarised here for completeness.

3.3.1 PVT Collector

The thermal and electrical outputs of the PVT collector (Type 50c) are computed using energy balance equations adapted from the Hottel-Whillier-Bliss formulation [18, 19]. The useful thermal energy gain Q_{th} is expressed as:

$$Q_{th} = A_c F_R\left[(\tau\alpha) \times G_T - U_L\left(T_{fi} - T_a\right)\right] \qquad (1)$$

where A_c is the collector area, F_R is the heat removal factor, $(\tau\alpha)$ is the effective transmittance-absorptance product, G_T is the total incident solar radiation, U_L is the overall heat loss, T_{fi} is the fluid inlet temperature and T_a is the ambient temperature.

The electrical output P_e is modelled as:

$$P_e = A_c G_T \eta_{ref}\left[1 - \beta\left(T_c - T_{ref}\right)\right] \qquad (2)$$

where η_{ref} is the reference electrical efficiency, β is the temperature coefficient of photovoltaic (PV) efficiency, T_c is the average PV cell temperature and T_{ref} is the reference cell temperature.

A key feature of the model is the thermal-electrical coupling within the collector. Heat transfer from the PV layer to the working fluid is explicitly modelled, making electrical efficiency sensitive to fluid flow dynamics. Higher flow rates enhance thermal extraction, lowering the PV cell temperature. This in turn increases the electrical output, as PV efficiency declines with rising cell temperature. This coupling highlights the importance of integrated system design and control in optimising both thermal and electrical performance in PVT-assisted configurations.

3.3.2 Vertical Ground Heat Exchanger

This component, based on the duct ground heat storage (DST) model reported in [20], represents a vertical U-tube borehole. It enables heat exchange between the ground and circulating fluid, providing a highly accurate analytical representation of thermal interactions within the subsurface. The interaction between the ground and the working fluid circulating in the borehole heat exchanger is modelled using TRNSYS Type 548a, which supports configurations for both vertical U-tube and tube-in-tube heat exchangers.

This component simulates the transient thermal response of the surrounding ground through a combination of three analytical solutions: a local solution, a global temperature field and a steady-flux approximation. The local and global thermal behaviours are solved using the finite-difference method, while the superposition principle is applied to compute the resulting ground temperature distribution over time.

3.3.3 Heat Pump

The water-to-water heat pump was modelled using TRNSYS Type 927 from the TESS library (rated heating capacity of 2 kW), which simulates single-stage operation based on manufacturer-provided performance maps. These maps define the system's heating and cooling capacities, along with power consumption, as functions of the entering source and load-side fluid temperatures. To facilitate practical heat pump operation, the source code of Type 927 was modified, resulting in a customised component named Type 9271. This new heat pump block enables modulation of the heat pump thermal power output by adjusting its electrical power input based on values between 0 and 1 [21].

The model interpolates performance data at each time step to determine the heat pump's operating point, allowing it to capture variations under off-design conditions. Source and load-side outlet temperatures are calculated based on standard energy balance using mass flow rates and specific heat capacities.

The adopted modelling approach provides an accurate and computationally efficient method for representing the heat pump's behaviour in transient simulations and ensures compatibility with the dynamic operation of the integrated PVT-GSHP system.

3.3.4 Thermal Storage Tank

A tank with capacity of 100 litres was modelled as a multi-node stratified volume and discretised into a set of horizontal isothermal layers (nodes), each representing a control volume. The model accounts for thermal interactions due to fluid mixing, conduction between nodes and heat exchange with the environment through the tank's top, bottom and side surfaces.

Each node's energy balance is governed by a first-order differential equation incorporating inflow/outflow energy, conduction to adjacent nodes, thermal losses and auxiliary heating input. Heat conduction between layers is modelled based on the thermal conductivity of the fluid and the temperature gradient across nodes. Environmental heat exchange is calculated using area-specific heat loss coefficients, allowing distinct ambient temperatures for each tank surface. This is described by

$$\frac{dT_{tank,j}}{dt} = \frac{Q_{in,tank,j} - Q_{out,tank,j}}{C_{tank,j}} \tag{3}$$

where $Q_{in,tank}$ and $Q_{out,tank}$ are functions of the ambient temperature and the inlet fluid conditions and flow rates. $T_{tank,j}$ is the temperature of the tank node, and C_{tank} is the capacitance of the tank.

The system of differential equations for all nodes is solved iteratively within TRNSYS using an approximate analytical method. While the solution approach is timestep-independent, it assumes average temperature values across each step to reach convergence for final and intermediate node temperatures.

3.3.5 Building Energy Balance

The multi-zone building model solves the following energy balance equation:

$$\dot{Q}_i = \dot{Q}_{surf,i} + \dot{Q}_{inf,i} + \dot{Q}_{vent,i} + \dot{Q}_{g,c,i} + \dot{Q}_{cplg,i} + \dot{Q}_{solair,i} + \dot{Q}_{ISHCCI,i} \tag{4}$$

where index i denotes the i-th air node, $\dot{Q}_{surf,i}$ is the convective gain from surfaces, $\dot{Q}_{inf,i}$ stands for the infiltration gain (air flow from outside only), $\dot{Q}_{vent,i}$ is the ventilation gain (air flow from a user-defined source, like a heating, ventilation and air conditioning system), $\dot{Q}_{g,c,i}$ is the internal convective gain (e.g. by occupancy, equipment, illumination, radiators) and $\dot{Q}_{cplg,i}$ is the gain due to (connective) air flow from air node i or boundary condition. Also, $\dot{Q}_{solair,i}$ is the fraction of solar radiation entering an air node through external windows and immediately transferred as a convective gain to the internal air, and $\dot{Q}_{ISHCCI,i}$ is the absorbed solar radiation on all internal shading devices of the zone and directly transferred as a convective gain to the internal air.

4. RESULTS AND DISCUSSION

Fig. 5 shows the thermal energy delivered by the GSHP to meet space heating demand during winter. The system exhibits a clear seasonal trend, with the highest thermal output recorded in January, corresponding to peak winter conditions (~58 kWh). The thermal load in November and December follows this trend but at reduced magnitudes due to comparatively milder outdoor temperatures and residual building thermal mass. The significant reduction in thermal energy exhibited in February and March reflects the declining heating degree days as the ambient temperature rises. These results highlight the GSHP's capacity to respond effectively to dynamic thermal loads while maintaining indoor comfort within defined temperature setpoints.

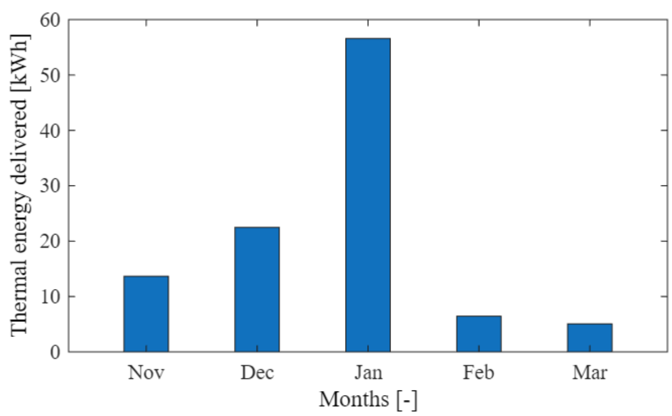

Fig. 5. Monthly thermal energy delivered by GSHP.

Fig. 6 shows the hourly variation in the GSHP's COP during a week in November and January, capturing system behaviour under differing ambient conditions. The COP profiles for both months show comparable peak values (~5.5), indicating consistent thermodynamic performance under winter conditions.

The operational periods, seen as blocks of elevated COP, coincide with increased space heating demand, showing well-regulated system activation. The clearly defined cycling pattern also indicates the controller's ability to regulate temperature within the desired setpoints without excessive short cycling. These results confirm the thermodynamic sensitivity of GSHP performance to seasonal variations and highlight the need for optimised system control to maximise COP under varying load conditions.

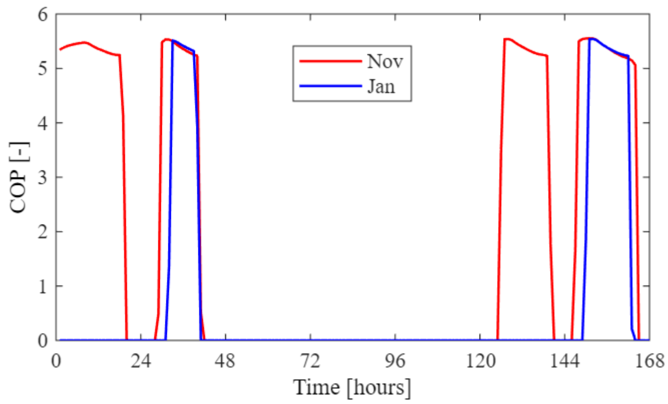

Fig. 6. Hourly COP of the GSHP during a representative winter week in November and January.

Fig. 7 shows the monthly thermal and electrical gains from the PVT collector during the heating season. Thermal gains dominate across all months, increasing from November to March, with a peak of approximately 9.5 kWh in March. This increase reflects the seasonal improvement in solar irradiance and longer daylight hours, which enhance thermal output even during low ambient temperatures. In contrast, electrical gains remain relatively low, with modest contributions in December and January. The reduced electrical output is attributed to lower solar angles and increased cell temperatures, which adversely affect PV efficiency.

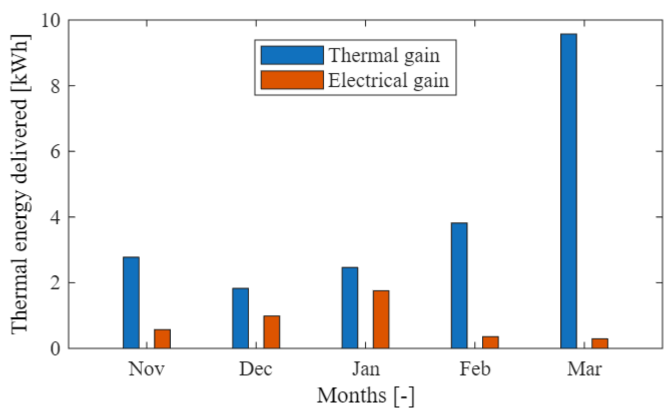

Fig. 7. Monthly thermal and electrical gains from the PVT collector.

Fig. 8 shows the inlet and outlet fluid temperatures of the PVT loop over a one-week period in January. The temperature profiles show clear diurnal patterns, with the outlet temperature consistently exceeding the inlet temperature, confirming effective heat pickup by the fluid from the PVT collector.

Peak outlet temperatures approach 13.8 °C while inlet temperatures remain slightly above 12 °C indicating a modest but stable thermal gain. The relatively narrow temperature differential reflects the low solar irradiance during winter and the limited thermal efficiency of the PVT module under colder ambient conditions.

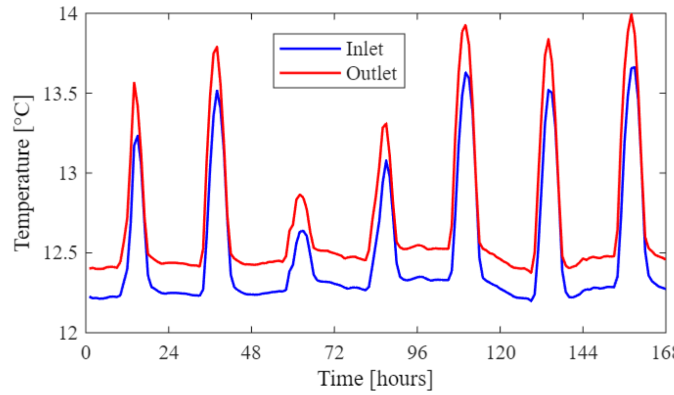

Fig. 8. Working fluid temperatures of the PVT collector during a representative week in January.

5. CONCLUSIONS

This paper evaluated the performance of a PVT coupled GSHP system for space heating using a dynamic TRNSYS simulation framework. The results demonstrate that the hybrid system can effectively meet winter heating demands in a UK residential dwelling, with the GSHP achieving stable and high COP during operation. The integration of PVT collectors offered both electrical and thermal benefits, contributing to improved system efficiency and partial regeneration of the ground loop.

The thermal energy delivered by the GSHP aligned well with seasonal load variations, with peak heating in January and limited demand during previous and successive months. While PVT thermal gains remained modest in winter, the consistent temperature differential across the collector indicated useful thermal recovery. Electrical generation was also sufficient to offset auxiliary loads in early heating months.

Control challenges relating to heat pump cycling were identified, highlighting the importance of optimised control strategies. However, the hybrid PVT-GSHP system showcased potential for low-carbon residential heating applications, especially when paired with appropriate control and sizing strategies.

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