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DYNAMIC SIMULATION OF SOLAR-ASSISTED AIR-SOURCE DUAL-LOAD HEAT PUMP SYSTEM FOR BUILDING SPACE HEATING AND COOLING

Summary

The adoption of renewable energy systems, particularly solar photovoltaics, in the built environment is essential for achieving global net-zero emission targets. However, mismatches between generation and demand often result in wasted surplus electricity or export to the grid, risking instability. Converting excess electricity into heat using an air-source dual-load heat pump (ASDLHP) integrated with underground thermal storage offers a practical solution. This study investigated a solar-assisted ASDLHP for inter-seasonal heating and cooling, incorporating simple control and operational strategies to effectively preheat source air and prevent frost-related losses. Simulations for an institutional building with 2,500 m² of rooftop solar showed a 25% increase in the seasonal coefficient of performance (SCOP) in winter, 9% in summer, and 20% overall energy savings compared with a conventional system. The system maintained year-round indoor comfort while effectively utilising surplus solar power.

Keywords: solar photovoltaic, solar-assisted heat pump, dual-load heat pump, heating and cooling, solar thermal

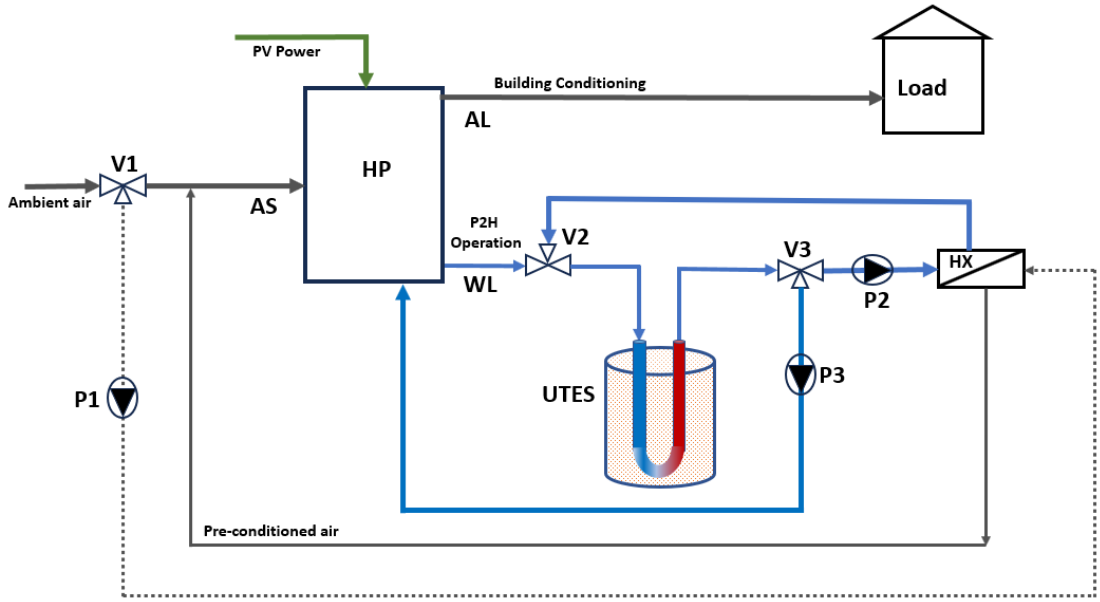
1. INTRODUCTION

The heating, ventilation, and air-conditioning (HVAC) sector is a major contributor to building energy consumption, accounting for roughly 45% of total demand and nearly 80% of related CO_2 emissions (Mousa et al., 2022). Solar-assisted air-source heat pumps (ASHPs) have been widely recognised as a promising solution to mitigate these environmental impacts, but their performance is often constrained by the mismatch between renewable generation and seasonal heating and cooling needs (Simonetti et al., 2020). During periods of low thermal demand, significant surplus electricity from photovoltaic (PV) systems is frequently curtailed, exported at low value, or stored in batteries with high cost and limited lifespan. These limitations motivate the integration of thermal energy storage, particularly underground thermal storage (UTS), to store surplus renewable energy for later use. However, most existing ASHP systems operate in single-load configurations, which restricts their ability to exploit surplus power for both immediate and future heating and cooling requirements.

This work presents a novel air-source dual-load heat pump (ASDLHP) system capable of delivering both air and water on the load side, enabling flexible inter-seasonal operation. In low-demand seasons, the ASDLHP operates in air-source water-load mode, converting surplus PV electricity into stored heat in UTES for future use. In high-demand heating and cooling seasons, the system operates in air-source air-load mode, using stored UTS energy to pre-condition source air and enhance the seasonal coefficient of performance (SCOP) and seasonal energy efficiency ratio (SEER). While dual-source or dual-load heat pumps have been studied in various applications, including solar-assisted systems, previous work has largely overlooked their combined use with inter-seasonal UTS in building-scale applications. This study addresses that gap by modelling and simulating an ASDLHP integrated with UTS, and comparing its performance to a conventional air-to-air heat pump without integrated UTS for Power-to-heat (P2H). The primary objectives are to evaluate the system's potential for increasing renewable self-consumption ratio, improving seasonal efficiency, and investigating the thermal efficiency of the UTS.

2. METHODOLOGY

The system was modelled using TRNSYS simulation tool with separate component representations for the building thermal and electrical load, PV generation, UTES, and heat pump operation as shown in Figure 1. The major components of the system configuration include the building thermal and electrical load model, solar PV model, UTES, and the heat pump. These models have been described in detail in the previous studies by Eze et al., (2024b). The building thermal load model was developed using lumped capacity Type88 model from the TRNSYS component library. Cooling and heating loads of 26.27 kWh/m^2 and 52.69 kWh/m^2, respectively, corresponding to typical school building was obtained. The building electrical load demand and consumption were modelled using the Type516 and grounded to a real usage pattern by measuring the base and plug loads on the actual building, which yielded 294 MWh and 145 MWh, respectively, corresponding to 33.6 kW base load and 54.8 kW plug-load per day (Kim et al., 2016). Solar PV model represented by the Type50 was designed to meet 30% of the load demand in the selected building using PV area of 2,500 m^2 at 21% module efficiency.



The UTS model was previously developed and calibrated with experimental data by Eze et al., (2024a), and its size was iteratively optimised to avoid freezing risks while maximising thermal efficiency. The heat pump was modelled using manufacturer performance data, with the ASWL and ASAL functions represented by TRNSYS Types 941 and 954, respectively. Seasonal operating scenarios were simulated for winter heating, summer cooling, spring power-to-cool, and autumn power-to-heat, with performance evaluated through surplus energy utilisation, self-consumption ratio, P2H/C efficiency, total energy savings, SCOP, and UTES thermal efficiency.

3. RESULTS AND DISCUSSION

Results show that the system maintained indoor comfort within 18–22 °C in winter and 22–26 °C in summer, matching conventional operation while enabling additional inter-seasonal storage functionality. Fig. 2 demonstrates the inlet air temperature to the heat pump for the traditional and test cases. The simulation shows that by applying the P2HC operation in spring and autumn, using UTES, the inlet air to the heat pump was preheated from -15 ℃ to 13 ℃ during the winter season and precooled from 35 ℃ to 13 ℃, temperatures capable of improving the heat pump performance. The UTS pre-conditioning significantly improved inlet air temperatures, raising them from –15 °C to 13 °C in winter and reducing them from 35 °C to 13 °C in summer, leading to an improvement of the SCOP (as shown in Fig. 3) by 25% and 9% respectively. Additionally, the system achieved overall energy savings of 20%, with P2H efficiency and UTS thermal efficiency of 31% and 34%, respectively. It maintained indoor temperatures within the control range across heating and cooling seasons, enabling effective P2H operations in spring and autumn. These results demonstrate an effective method for utilizing surplus solar PV power in the built environment while fully mitigating heat pump performance losses due to defrosting cycles.

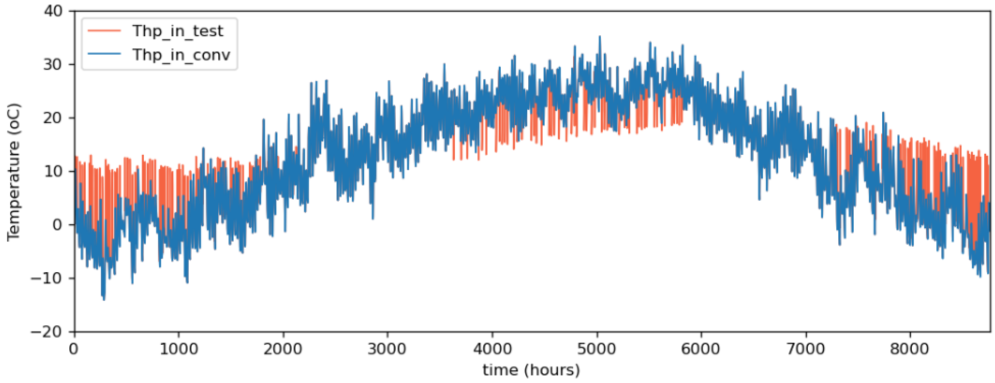


Fig. 2: Inlet (source) air to the heat pump for test and conventional cases

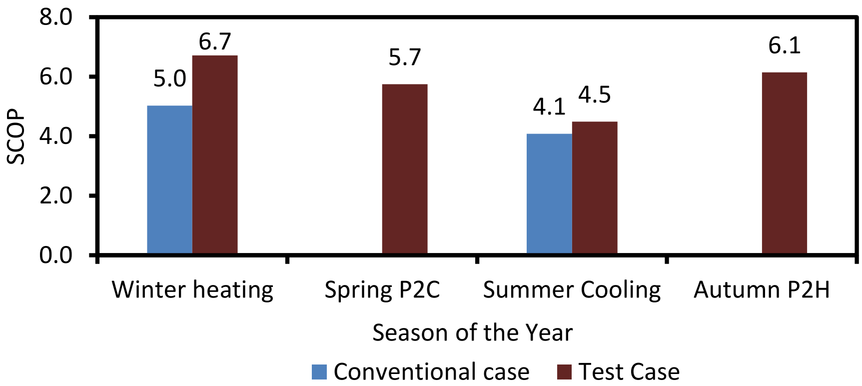


Fig. 3: SCOP comparison for test and conventional cases

4. CONCLUSION

The proposed ASDLHP with UTES provides a technically viable solution for inter-seasonal utilisation of surplus solar energy in buildings, offering both heating and cooling while enhancing renewable self-consumption. The approach delivers notable improvements in seasonal efficiency and energy savings, with performance benefits through mitigation of defrosting challenges. These findings demonstrate the potential of integrating dual-load heat pumps with underground storage to address the seasonal mismatch challenge and contribute to more sustainable building energy systems, improving heat pump perfromance.

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