

## **Title: Novel Thermal Energy Storage Integrated Ground Source Heat Pump System for Grid-interactive Efficient Buildings**

### **ABSTRACT**

To reduce greenhouse gas emissions, shifting the energy sources used in buildings, transportation, industry, etc., from fossil fuels to clean electricity is a trend. The increasing electricity demand stresses the existing electric grids. Buildings consume 74% of all U.S. electricity and are responsible for 30% of U.S. greenhouse gas emissions. Residential and commercial buildings' space heating/cooling system consumes considerable electricity. Integrating thermal energy storage (TES) in building heating/cooling systems can mitigate the challenge of electric grids. Applying TES to existing air-source heat pump (ASHP) systems is the most studied for residential buildings. However, the high-quality thermal energy requirement for charging the TES tank results in low thermal performance of the ASHP system. Moreover, the failure of ASHP in cold climates requires a supplemental electric heater that significantly reduces the system efficiency and may lead to a higher annual peak for the grids.

This study proposes integrating TES with ground-source heat pump (GSHP) systems as a more effective solution for building decarbonization due to the high efficiency of renewable-energy-based GSHPs year-round. This study focuses on proving the effectiveness of TES-integrated GSHPs for building decarbonization. A dual-source heat pump (DSHP) with a hybrid TES and ground heat exchanger (DPUTB) is investigated. The study uses modeling and experiments to verify the system's energy efficiency, decarbonization potential, and demand response capability. The modeling process involves developing various models, from component-level to system-level, and investigating advanced control strategies. A first-of-this-kind dynamic model of the DPUTB is developed to enable high-resolution system simulation for the GSHP system. The simulation is conducted using Modelica with rule-based control (RBC). A model predictive control (MPC) is also developed based on dynamic building envelope and HVAC system models. A cutting-edge co-simulation testbed integrates Modelica physical models with a MATLAB MPC controller model for advanced control evaluation. A prototype system of the DPUTB+DSHP is tested in a flexible research platform at Oak Ridge National Laboratory, which allows for component and system-level testing and remote automation controls.

The study highlights the importance of proper insulation in the performance of the DPUTB, which consists of a TES tank enclosed by an outer tank functioning as a ground heat exchanger. With appropriate insulation, a full-size DPUTB can store 1-ton cooling (3.5 kW) for four hours after eight hours of charging. Simulation results suggest that decoupling the TES with the ground heat exchanger could reduce energy consumption by 27%. System-level simulations confirm that the DSHP+DPUTB system, with a customized RBC, outperforms the conventional ASHP. The proposed system can reduce the annual heating, ventilation, and air conditioning (HVAC) electricity cost by up to 50% while saving 45% on electricity consumption. In the Northern areas of the United States, the annual peak load of the HVAC system can be reduced by 60%. However, this reduction is less in the Southern parts of the United States as the system's higher efficiency in winter dominates the overall decrease. The application of MPC can further reduce the cost and energy consumption of the system by 35% theoretically. However, the accuracy of model prediction affects its performance in practical applications, which can be mitigated by employing technologies such as machine learning and reinforcement learning. Further research is required to verify these technologies.

The DSHP+DPUTB system, a type of TES-integrated GSHP, has been well-designed and demonstrated superior performance to conventional systems, with greater flexibility and thermal efficiency. As a result, this system can enable electrification in the space heating sector without requiring an escalation in the grid. Moreover, alternative controls can be utilized to exploit its decarbonization potential fully.