Energy Modeling and Performance Evaluation of Hybrid-Source Heat Pumps with Solar Thermal and Radiative Cooling for Decarbonized Space Heating in Cold Climates

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Abstract:

Decarbonizing and electrifying residential space heating is critical for reducing carbon emissions and enhancing energy security in extreme cold climates. This study presents the development of an energy model to evaluate the performance of a hybrid-source heat pump system integrated with solar thermal collectors, radiative sky cooling, and a thermal storage water tank. The model incorporates COP data from a cold climate air-source heat pump tested and analyzed by the authors. A Python-based simulation framework was developed to analyze various HVAC configurations using TMY3 weather data, performance data from commercially available equipment, and historical energy pricing. The proposed hybrid system was compared against conventional heating oil boilers, as well as single and dual air-source heat pumps and water-source heat pumps with similar integrations. Results demonstrated that the hybrid-source heat pump system significantly reduced heating oil consumption by 43.1% and operational costs by 19.12% compared to the baseline system. While all tested configurations exhibited reductions in CO_2 emissions and reliance on fossil fuels, a benefit-cost analysis indicated that increased maintenance costs could offset operational savings. This work highlights the potential of hybrid-source heat pumps with advanced thermal management strategies as a viable pathway for decarbonizing space heating in cold climates.