BEST Center Funded Research Summary

Combined Design and Control Optimization of Energy Systems to Aid Electrification of Residential Buildings

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Motivation

Standard methods for designing energy systems in new construction residential buildings usually determine thermal loads using standard rule-based control schemes. It is only after specifying energy system capacities and installation that optimized control strategies are considered. Research shows these design approaches often result in oversized equipment, such as heating and cooling systems, leading to difficulty maintaining thermal comfort and reducing peak demands. The objective of this project is to investigate the energy and cost benefits of simultaneously optimizating the design and control of building energy systems for projects involving electrification of residential buildings. This approach could lead to more effective design procedures for building energy systems to minimize initial costs, operational costs, and carbon emissions.

Methods

Using a whole building energy analysis tool (EnergyPlus) coupled with well calibrated building energy models, the combined optimization procedure was first tested for the design and control of heat pumps. Then, a more extensive set of building energy systems was evaluated, including domestic hot water heaters, PV arrays, and batteries. Figure 1 shows the analysis approach for the combined optimization of heat pump sizing in Energy Plus.

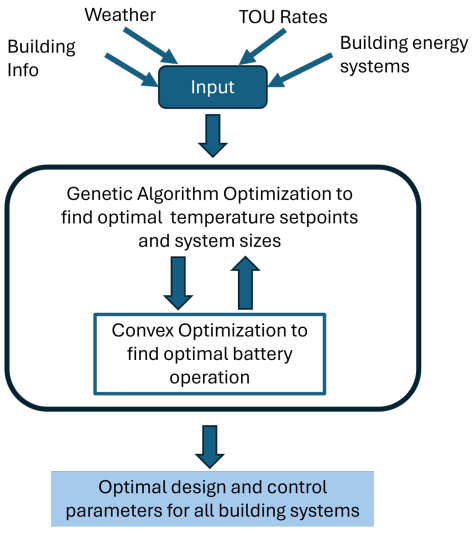

Figure 1. *Combined analysis approach considered throughout the project*

A grey-box modelling package developed by NREL (OCHRE) was used for modelling residential building energy systems. High-fidelity models with prototypical performance maps were used to simulate the energy systems, and setpoints were used as the control parameter, allowing the methods to still be practical in realistic use cases.

About the BEST Center

The Building Energy Smart Technologies (BEST) Center is a partnership between the University of Colorado Boulder and City College of New York operating using the NSF's industry-university cooperative research center model. The center fosters interdisciplinary collaborations between the building industry and university research to advance energy systems through university-industry partnerships to engineer the intelligent and efficient cities of tomorrow.

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Results

First, the energy benefits of combined design and control optimization of heat pumps were compared to the "design only" and "control only" optimizations. Figure 2 illustrates the HVAC energy savings for two indoor thermal discomfort levels and the three optimization options for a prototypical detached home located in Denver, CO.

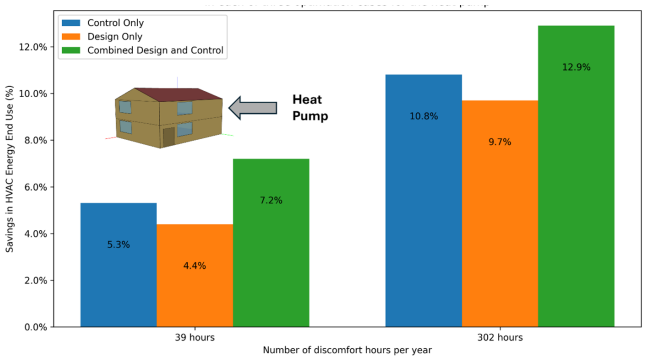
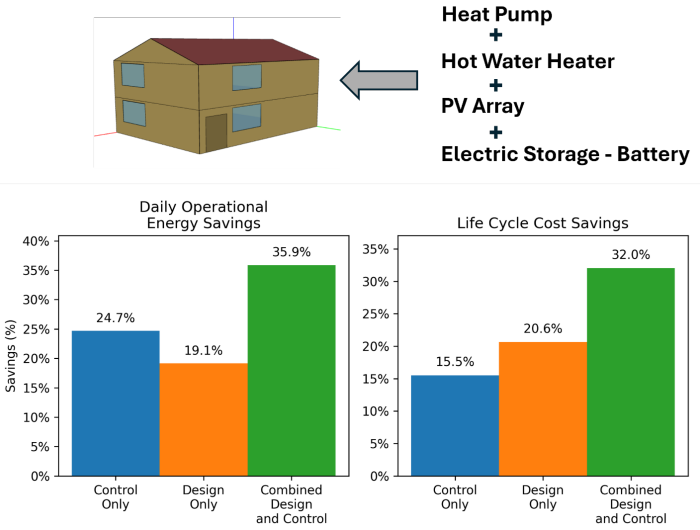


Figure 2. *Annual energy savings relative to the baseline of a prototypical home in Denver, CO, associated to three optimization cases: (i) design only, (ii) control only, and (iii) combined design and control, for two desired sets of indoor thermal discomfort hours (Vadali and Krarti, 2025).*

For a higher thermal discomfort level (i.e., 302 hours), the combined design and control optimization achieves **13%** reduction in annual HVAC energy use, relative to the "control only" (11%) and "design only" (10%) optimizations. Energy savings increase considerably when multi-speed heat pumps are used, reaching up to **20%** for combined design and control optimization (Vadali and Krarti, 2025).



When considering multiple energy systems (heat pumps, hot water heaters, PV arrays, and electric storage batteries) for the same detached home, the combined design and control optimization outperforms individual design and control only optimizations, reducing both capital and operating costs, as well as energy costs, as shown in Figure 3. The combined design and control optimization achieves reductions of **35.9%** in energy use and **32.0%** in life cycle costs during a winter design day of the detached home.

Figure 3. *Comparison of energy savings and life cycle cost reductions obtained from three optimization cases (i) design only, (ii) control only, and (iii) combined design and control for a prototypical detached home equipped with a heat pump, a hot water heater, a PV array, and an electric storage battery during a winter design day in Denver, CO, and subject to a Time of Use (TOU) rate.*

Next Steps

The next phase of this project will integrate this optimization methodology into a retrofit analysis tool, also developed through BEST Center funding. This analysis will be extended to consider additional constraints, such as electrical power ratings and budget limit cost functions to optimize the design and control strategies of building energy systems for electrification retrofit projects in both residential and commercial buildings.

Research Products

1. Phani Arvind Vadali, Moncef Krarti (2025). Combined design and control optimization of heat pumps in residential buildings. *Energy* 236, https://doi.org/10.1016/j.energy.2025.136317.
2. Phani Arvind Vadali, Moncef Krarti, Combined design and control optimization of multiple energy systems in residential buildings, 2024, *In Preparation*.