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Final Technical Report (FTR)

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Executive Summary

This study examines a residential dual fuel (DF) heating system that integrates heat pump and gas furnace technology with a home's forced-air distribution ducts. Specifically, it explores a retrofit where an "add-on" heat pump replaces the air conditioning (A/C) system and is combined with the home's existing furnace and air handler. The research team developed and validated an innovative control scheme for this integrated DF system that selected the more economical heating source (furnace or heat pump) while maintaining comfort in the home. The project's field study and subsequent modeling analysis show that this control scheme can decrease energy use, cost, and emissions compared to a furnace-only system. As homes in mixed and cold climates transition to more electric space heating, furnace-to-dual fuel system retrofits offer a solution that can alleviate the retrofit costs, energy cost concerns, and peak load impacts of full electrification.

The project consisted of four major phases. In the initial phase, the project team convened an Advisory Group (AG) comprised of HVAC manufacturers, utilities, and efficiency programs. The AG provided review, insights, and feedback throughout the project on the research design and project findings. The project team developed the DF heating system control logic based on analysis and dialogue with DOE and the AG. During Phase 2, the project team performed a field evaluation in which an existing cold climate home was selected for detailed pre- and post-retrofit heating system performance monitoring. The retrofit was installed in between the two winters of monitoring and involved replacing the home's existing A/C system with an add-on heat pump sized to address the home's design heating load and with the ability to integrate with the existing furnace and blower. In the third phase, the project team calibrated EnergyPlus simulation models using field data from the test site. This work occurred during the initial winter of the field study (when the existing furnace-only system was operating) and the second winter (when the dual fuel heating system was operating). In Phase 4 the team leveraged the calibrated models to broaden the evaluation of DF heating systems. The scaled-up modeling analyzed DF system performance in additional climate zones and assessed the implications of varying key design parameters including the control logic, heat pump capacity, building tightness, and energy rates.

The specific type of retrofit application examined in this study, in which an A/C system at the end of its life cycle is replaced with an add-on heat pump compatible with the home's existing furnace and blower, is both technically and economically feasible. The analysis provides insights on the performance implications of several design variables (e.g., heat pump capacity, building tightness) that can be applied by stakeholders immediately. It is anticipated that control options similar to the logic developed in this project will become increasingly available in the market.

The findings from this work provide valuable and unique insights to key stakeholders involved in residential heating system deployment including utility energy efficiency program managers, HVAC manufacturers, efficiency organizations, researchers, and homeowners.

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Background

The nation's energy landscape is changing and many states, utilities, and efficiency programs within the U.S. are mobilizing to increase renewable energy generation, improve buildings' energy efficiency, and increase electrification of building loads. Space heating is one of the primary targets for these efficiency and electrification efforts. Heat pump technology has advanced significantly in recent years and now delivers high efficiency levels while maintaining capacity at cold ambient temperatures. While this technology is widely available, more than 38 million U.S. homes in the mixed and cold climate regions of the U.S. (about 48% of the housing stock) utilize a gas-fired forced-air heating system (Office of Energy Demand and Integrated Statistics, 2024). Heating cost impacts, retrofit costs, grid integration, reluctance to replace newer furnaces, and consumer concerns about relying solely on a heat pump for heating are issues that can impede wider electrification in these homes. "Dual fuel" heating systems, as evaluated within this project, provide energy choice and can help to alleviate these challenges.

This study examines a dual fuel heating system that integrates heat pump and gas furnace technology with the home's forced-air distribution ducts. The application researched in this project is a retrofit in which an "add-on" heat pump replaces the existing A/C system and is combined with an existing furnace and air handler in the home. The controls for both the furnace and heat pump are integrated into a single set of controls. This add-on heat pump application is illustrated in Figure 1.

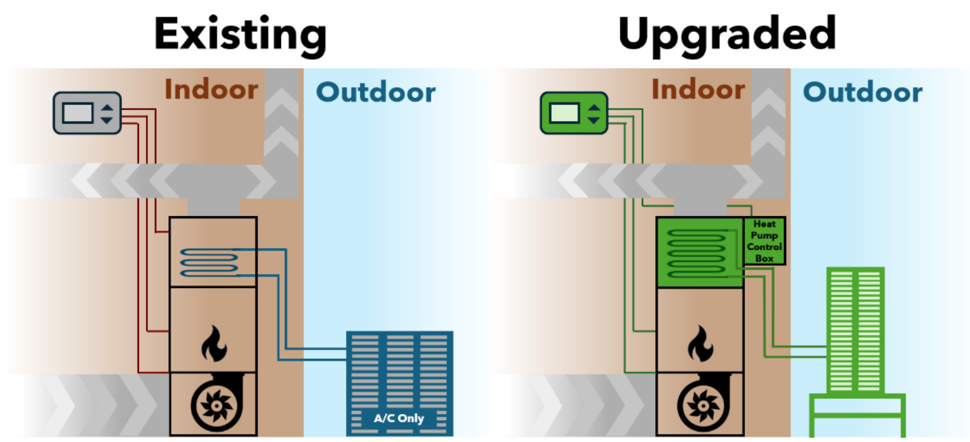

Figure 1. Retrofit application of replacing the existing A/C system with an add-on heat pump, which is integrated with the home's furnace.

Other types of residential dual fuel heating systems, which are not the focus of this research, include:

- Heat pump systems in tandem with hydronic heating systems. An example is an existing home with original hydronic heating in which an air-based heat pump has been added to address some of the heating load. The heat pump may be ducted for distribution or be ductless. The controls for this type of configuration are typically not integrated.
- Complete systems in which both the heat pump and the furnace are from the same manufacturer, have integrated controls, and are provided as a combined

system. These systems are an option in both new and existing homes and typically have a significantly higher cost than the add-on heat pump.

There are multiple benefits to the add-on heat pump configuration shown in Figure 1. In some scenarios, adding a heat pump may provide cooling to the home for the first time or replace window A/C units with centralized heat pump-based cooling. This may occur in areas that historically did not have significant cooling needs but now require space cooling due to rising summer temperatures. Additionally, the add-on configuration can serve as a bridge technology to achieve energy and environmental goals while effectively navigating implementation challenges.

However, the control scheme typically used in this add-on application hinders the dual fuel system's efficacy. The traditional control scheme for dual fuel heating systems uses only a static switchover temperature. Below this switchover temperature, the furnace will provide heating, and above this temperature, the heat pump is enabled to meet the home's heating load to the extent possible. The switchover temperature is often set conservatively at 40° F to minimize potential comfort complaints or to ensure the heat pump can meet the home's heating load. This type of control scheme does not leverage dual fuel systems' potential to optimize energy consumption, cost, demand, emissions, and grid integration. The project described in this report focused on characterizing the performance benefits that are possible with dual fuel heating systems (in a retrofit application) controlled with a more innovative control logic.

Several existing resources informed this project, including research, policies, and codes related to the implementation, control, and energy and cost implications of dual fuel heating systems. Relevant research also examines broader issues like energy rate structures and incentives. The sections below describe how this project builds upon and contributes to this body of work and broader market implementation.

Figure 2. Factors affecting dual fuel heating system implementation.

Research on Dual Fuel Heating System Controls

Demirezen and Fung (2021) explored the potential of combining heat pumps with natural gas furnaces to reduce emissions and lower operational costs. This research focused on the application of this technology to Canadian homes, and included a cloud-based switching algorithm which incorporated weather forecasts via an API. The analysis methodology also incorporated assumed carbon pricing levels.

This research had a similar focus to our current project, which was initiated in September 2020 prior to Demirezen and Fung being published. For example, both studies integrated time-of-use (TOU) electric pricing strategies to offer the dual fuel system the opportunity to leverage heat pump operation during periods of lower costs. This opportunity can be significant in reducing overall system operating costs.

The current project also offers complementary insights by focusing on the retrofit of existing heating systems and incorporating a field study component to evaluate a real-world retrofit. This element of the project allowed the research team to evaluate system integration considerations such as selecting an appropriate add-on heat pump to integrate with the existing furnace and blower (see Milestone 3.3 for more discussion on these topics). Additionally, the field study yielded a clearer understanding of system operations under real-world conditions, providing insights on issues such as defrost cycles and their impact on indoor temperature, thermostat setback and its impact on heat pump operation, and system performance at design conditions. Characterizing these aspects of system performance at the field site was instrumental in the development of a calibrated simulation model. This simulation model then allowed for the exploration of several additional variables, such as heat pump capacity and building tightness, in three different climate zones without further costly and lengthy field trials.

When our project was initially proposed and started, there was limited (if any) recent research with a similar focus. The Demirezen and Fung work demonstrates additional interest in dual fuel heating system applications and the potential energy cost benefits of this technology.

Codes and Above-Code Programs

The U.S. EPA's NextGen program is a voluntary, above-code program that recognizes homes with high efficiency electric technologies that reduce both energy use and operational emissions. However, NextGen does not mandate an all-electric home design; the program allows the use of dual fuel heating systems for space heating. This allowance shows the potential role for this technology. The NextGen program does not currently provide guidance on controls or best practices for the installation of dual fuel systems (ENERGY STAR Residential New Construction Program, n.d.).

The 2024 International Energy Conservation Code (IECC) is a model energy code which was published in mid-2024. This latest edition of the IECC (updated from the 2021 IECC) includes new requirements for supplementary heat used in conjunction with heat pump systems. Section R403.1.2 (heat pump supplementary heat) addresses both electric resistance backup heat and gas-fired supplementary heat (ICC, 2024). The requirements prioritize operation of the heat pump to address the heating load and restrict the use of the supplementary heat source to times when the heat pump cannot meet the thermostat setting or complete defrost cycles, or there is a mechanical failure of the vapor compression cycle or the thermostat. These provisions are more restrictive than the control scheme researched in this project and could impede similar innovative control strategies that can potentially improve system performance and reduce energy costs. The impact of these provisions will depend on the heat pump's capacity relative to the home's heating load as well as how these requirements are adopted and enforced. In future code update cycles, such as the 2027 IECC, this language should be revisited to allow for dynamically controlled dual fuel systems.

Electric Rate Policies

Some utilities are introducing new electric rate structures that encourage households to adopt heat pumps for winter heating. For example, in July 2024, Massachusetts regulators approved a local utility's plan to offer a lower volumetric distribution rate during the winter for households with heat pumps, with an additional 40% discount for low-income households (Kresowik, 2023). In Minnesota, another utility (Xcel Energy) proposed a lower volumetric distribution rate during the winter for homes with electric space heating. This proposal also featured a three-tier time-of-use (TOU) rate to incentivize electricity use during off-peak hours and included automatic discounts for low-income households (Xcel Energy, 2023). Rate design features like these align incentives with efficiency goals and reflect a trend of policies that support heat pump adoption.

Electric rate policies with TOU pricing can incentivize broader dual fuel system adoption, and this study illustrates their potential effectiveness by deploying and demonstrating a dual fuel system with smart controls that can leverage time-varying electric rates to save energy and costs.

Utility Industry Efforts

The Consortium for Energy Efficiency (CEE) and its Emerging Technologies Collaborative is actively exploring integrated residential HVAC system controls, including dual fuel applications. Their members (primarily utilities) are articulating their needs for integrated controls and evaluating current marketplace options. Staff from this project have shared and discussed our project findings with CEE to contribute to this effort.

Additionally, the project team has anecdotally learned of utility programs that have implemented dual fuel retrofit programs. The goal of these programs is to lower emissions from home heating, and in some cases, to add cooling to a home for the first time in the interest of resilience in mixed/cold climates where summer cooling has become a pressing need.

Research on electrification of space heating and the implications for peak load and grid management is also relevant to this project. While control-optimized dual fuel heating systems can be a useful technology for energy and cost savings across mixed and cold climates, the application explored in this research can be especially relevant to regions where electrification is projected to change peak demand. The *Electrification Futures Study*, published by the National Renewable Energy Laboratory (NREL) in 2018, predicts that the New England and Mid-Atlantic regions are likely to see peak loads shifting from summer to winter due to the adoption of heat pump-based heating systems (Figure 3), and concludes that "These changes [in peak demand timing and magnitude]…could have significant impacts on electric utility planning, grid operations, reliability assessments, and electricity markets" (Mai, et al., 2018).

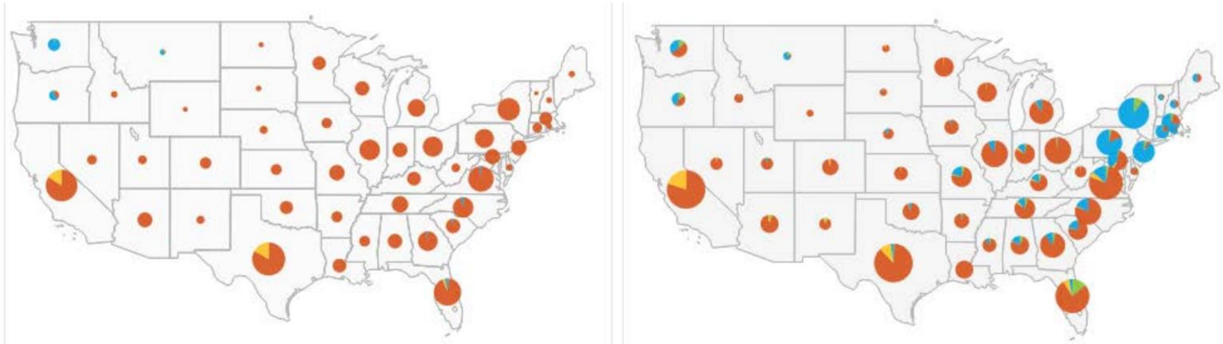

Figure 3. Peak load size and seasonal timing by state, 2015 and 2050. Orange indicates summer: blue: winter; green: spring; and yellow: fall. Under a high electrification model, the northeast in 2050 is dominated by winter-time peak loads.

While this project does not focus on grid-interactive dual fuel heating systems, deploying smart, dual fuel heating systems in existing homes does offer a way to manage changing grid dynamics, and the results of this study can inform work on future grid-interactive controls for dual fuel heating systems.

Overall, this project complements ongoing developments in the industry by providing insights on the performance and potential benefits of innovative controls for dual fuel heating systems in retrofit applications.

Project Objectives

This project was designed to develop an optimized control scheme for a dual fuel heating system in a retrofit application and demonstrate its effect on efficiency gains and energy cost savings. Effectively demonstrating and promoting these benefits to stakeholders can facilitate increased integration of dual fuel heating with advanced controls into utility incentive programs and energy efficiency programs, accelerating cost-effective retrofits in existing homes. These outcomes support DOE's priorities on cost savings and energy choice.

Indicators of success for this project include:

- increased market availability of add-on heat pumps (potentially with advanced controls) tailored for retrofits of existing forced-air furnace and A/C systems
- increased recognition, incentives, and/or requirements for these technologies in utility programs, non-utility efficiency programs, affordable housing programs, and stretch codes

The major phases of the project are shown in Figure 4 below. In the initial phase, the project team first developed and convened an Advisory Group (AG) comprised of HVAC manufacturers, utilities, and efficiency programs. The AG provided review, insights, and feedback throughout the project on the research design and project findings. During Phase 1, the project team also developed potential approaches for the control logic for the dual fuel system. After discussions with DOE and the AG, a final control logic was selected and developed further for use in the field evaluation (Phase 2) and subsequent modeling analysis (Phase 4). The project team conducted modeling to estimate the performance impact of controlling the dual fuel heating system using this control logic.

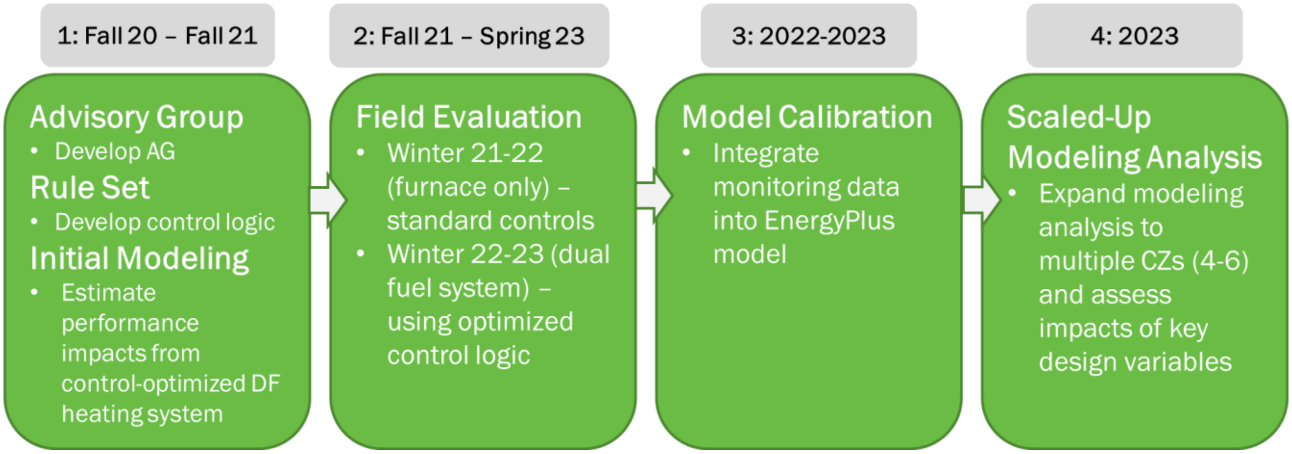

Figure 4. Major project phases.

In Phase 2, the project team completed a field evaluation by first facilitating the installation of a dual fuel heating system with an add-on heat pump and then performing detailed monitoring to characterize system operations and efficiency. Conducting the field evaluation required:

- identifying and recruiting a representative existing home in a cold climate, with adequate access for a 2-year period (coming out of the COVID pandemic).
- instrumenting the home with monitoring equipment to measure and record all relevant environmental conditions, energy inputs, and system operating metrics.
- assessing potential add-on heat pumps to install that would integrate with the home's furnace and have suitable heating and cooling capacities to align with the home's loads, while also meeting a significant portion of the home's heating load.
- interfacing with the heat pump manufacturer to understand how we could control the dual fuel heating system using the project's customized control logic (effectively overriding some of the manufacturer's control logic).
- programming a datalogger with the control rule set and using specialized electronics to allow the rule set to control the dual fuel system operations.

During Phase 3, the project team calibrated the EnergyPlus model using field data from the test site. This work occurred during the initial winter of the field study (when the existing furnace-only system was operating) and the second winter (when the dual fuel heating system was operating).

Phase 4 produced the scaled-up modeling analysis. The project team leveraged the calibrated model developed through the field study to broaden the analysis of the dual fuel heating system. The scaled-up modeling covered additional climate zones and varied key design parameters including the control logic, heat pump capacity, building tightness, and energy rates.

The project milestones and Go / No-Go decisions, as articulated in the project SOPO, are shown below in Table 1. Note that the project SOPO and work scope did not include a detailed assessment of dual fuel market potential, creating detailed guidance on furnace-to-dual fuel retrofits, development of proprietary control functionality, or a detailed evaluation of a specific heat pump technology operating under its own commercial control system. These lines of research may be considered for future work.

Table 1: Project Milestones and Go / No-Go Decisions

Task	Task Title	M/GNG	Description	Verification	Due Date
1	Engage Advisory Group	M1.1	Roster of Advisory Group members containing no less than the targeted number and type of participants.	Roster in Excel format	1/1/2021
2 (A, B)	Develop Co-optimized HHP Control	Task 2A M2.1	Logic model illustrating OHC operation and decision hierarchy across various environmental conditions and user/utility configurations.	PDF of logic model submitted with Q report.	4/1/2021
		Task 2A M2.2	Quantification of targeted metrics from performance simulations of multiple configurations, addressing targeted metrics as compared to reference scenario of furnace-only operation.	Q report summarizing results for targeted metrics.	7/1/2021
		Task 2B M2.3	Programmed logic model to be used by the OHC.	Program text and file submitted with Q report.	1/1/2022
		GNG1	≥ 35% energy savings for the HHP with the OHC in ≥ 1 configuration vs. a furnace in a cold climate location.	Doc summarizing simulation results.	7/31/2021
3 (A, B, C)	Validate and Analyze the HHP with OHC	Task 3A M3.1	Cold climate test site recruited, screened, and instrumented with the data acquisition system for the first heating season.	Verification of homeowner agreement submitted with Q report	7/1/2021
		Task 3B M3.2	Data analysis from first heating season, including heating equipment time of use, site energy use (and associated source energy use estimate), emissions estimate, and climatic data.	Q report summarizing heating demand & energy use.	6/1/2022
		Task 3B M3.3	HHP with OHC installed and commissioned with the data acquisition system (DAS) for the second heating season.	Receipt from HHP install, summary of DAS submitted with Q report.	9/15/2022
		GNG2	Demonstrate savings for the control-optimized heat pump of at least 35% versus the reference case of a fossil-fuel fired furnace, based on analysis conducted with an energy simulation model that has been calibrated with the test site's field monitoring from Winter #1.	Q report summarizing results for SMART metric.	9/1/2022

Task	Task Title	M/GNG	Description	Verification	Due Date
		Task 3C M3.4	Data analysis from second heating season, including heating equipment time of use, site energy use (and associated source energy use estimate), emissions estimate, and climatic data.	Q report summarizing results for targeted metrics listed in Task 2.	6/1/2023
4	Conduct Modeling to Broaden Applicability of In-Situ Testing Results	Task 4 M4.0	Outline of scaled-up modeling to identify scope and metrics	PDF	9/30/2023
		Task 4 M4.1	Normalized, climate-specific results from building energy simulations identifying performance of HHP versus the reference case.	Q report summarizing building energy simulation results.	4/1/2024
5	Manage Project & Disseminate Results	Task 5C M5.1	Utility guidance document for establishing minimum functionality and feature specifications for OHCs, also including information on criteria for appropriate homes.	PDF	7/30/2024
		Task 5C M5.2	Conference presentation/webinar for utilities, efficiency organizations, and regulators summarizing final results.	PPT	6/30/2024
		End of Project Goal	Final report demonstrating full-season normalized energy savings of 45% vs. a furnace and ≤ 3% of heating season hours with > 3° F deviation between t-stat set point and room air temperature.	PDF	8/31/2024

Project Results and Discussion

The project results are presented in this section using the milestones listed in Table 1 as the framework. Milestones and Go / No-Go decision points are listed below along with a discussion of the project results correlating to that point in the research.

Milestone 1.1: Roster of Advisory Group members containing no less than the targeted number and type of participants.

This milestone was due by 1/1/2021 and was completed by 12/28/2020. A listing of the organizations represented on the project Advisory Group (AG) is included in Appendix A. As proposed, the project team recruited and convened HVAC manufacturers (e.g., Johnson Controls, Mitsubishi), utilities (e.g., Eversource, Xcel), and energy efficiency organizations (e.g., Consortium for Energy Efficiency) to form a group with various important perspectives for this project. The AG also included several representatives from DOE national labs to help connect this effort with related work underway by DOE. The team continued adding industry members to the AG over the course of the project.

The project team engaged with the Advisory Group at key points in the project, such as during the initial development of the control logic and during scope development for the scaled-up modeling analysis. The AG provided valuable insights and feedback throughout the project. Examples include:

- Guidance on the development of the control rule set and noting the importance of the project validating the potential benefits of dual fuel heating systems compared to furnace-only systems.
- Providing insights on the details of dual fuel system operations.
- Offering perspectives on how utilities view the potential implementation of dual fuel heating system retrofit programs.

Milestone 2.1: Logic model illustrating Optimized Heating Control (OHC) operation and decision hierarchy across various environmental conditions and user/utility configurations.

This milestone was due 4/1/2021 and was completed on 4/1/2021. This milestone constituted development of the control logic concepts, or “rule set,” which would determine which heating source in the dual fuel system (furnace or heat pump) would respond to a heating call in the home. A more detailed graphical illustration of the final control logic is found in Appendix B (which corresponds to Milestone 2.2).

Based on extensive dialogue within the project team and with the Advisory Group, the following objectives were formed for the control logic:

Primary Control Objectives:

- To decrease the heating system operational cost to the homeowner with the Dual Fuel heating system as compared to a furnace-only baseline system.
- To maintain comfort in the home in terms of indoor temperature versus thermostat set point.

Secondary Control Objectives:

- To lower emissions associated with home heating by enabling the lower emitting heating source at a given point in time, if the cost to heat with the heat pump is comparable to the cost with the furnace.

Logic Description:

When there was a call for heating, the rule set determined if the heat pump or the furnace would respond to the heating call. Simultaneous operation of the furnace and the heat pump (which was located downstream from the furnace) did not occur due to potential negative impacts on the heat pump.

1. Maintaining Temperature. During all periods other than recovery following thermostat setback (if used), maintaining the indoor temperature within 2° F of the thermostat set point took priority over other rules. If the heat pump was enabled but this limit could not be maintained, an auxiliary subrule based on heating rate would be triggered. If the heat pump was able to increase the indoor temperature at a sufficient rate, then it would be allowed to continue providing heat. Furnace operation would be triggered based on indoor temperature if and only if the indoor temperature fell sufficiently far below the thermostat setpoint *and* recovered at a sufficiently slow rate. The research team planned to incorporate this indoor temperature rule into the control logic implemented at the field study test site, but it was already included in the native controls of the Mitsubishi heat pump.

"Next Chance Logic." For Rule #1, the control also accounted for when the heat pump will be given a "next chance" if it had been previously locked out due to the inability to maintain temperature. The initially planned "next chance" logic incorporated a static lockout period of 30 minutes in the initial control logic and modeling. In practice at the field site, the native controls of the heat pump took precedence in determining when the heat pump could provide heating again following an episode when it did not meet heating requirements.

This "next chance" logic was necessary to prevent the heat pump from being enabled immediately after repeatedly failing to satisfy Rule #1, which could cause comfort issues.

2. Evaluation of Heating Cost Effectiveness. The heat pump heating efficiency (COP) was estimated based on a performance curve in tandem with time-dependent energy costs to determine cost per BTU of heating for the heat pump. This value was compared to the furnace cost per BTU which was based on the furnace efficiency (assumed to be static) and the price of natural gas (assumed to be static). The heating source with the lower cost per BTU was selected as the economical option to provide heating at that time.

Both the field evaluation and modeling analysis assumed electric pricing with Time of Use (TOU) rates. This rate structure is increasingly available to residential customers and demonstrates the dynamic control logic's ability to optimize heating energy costs. This study's specific TOU rates were based on a composite of 3-tier residential utility rates in several mixed/cold climate markets. After the field evaluation, the rates were updated based on a sample of current residential rates (see Milestone 4.1 for more details).

If Rule #1 was satisfied and the heat pump was more economical to operate, then the heat pump was selected to respond to heating calls. If Rule #1 was not satisfied and/or the furnace was more economical to operate, then the furnace was selected to respond to a heating call. This selection was re-evaluated for each heating call occurrence.

3. Select based on emissions (in limited cases). If Rule #1 was satisfied, and Rule #2 resulted in the heat pump costing no more than 10% more than the furnace, then the heating source with the lower emissions (at a given point in time) was selected as the heating source.

The initial control logic also included provisions to address the recovery period that followed a thermostat setback period. At these times, the indoor temperature would be several degrees lower than the current set point temperature. During the field study, the add-on heat pump's native control functionality during recovery periods (which could not be bypassed or overridden) resulted in system operations that excluded heat pump operation for significant periods of time. As a result, the field study was adjusted to eliminate the use of thermostat setback. Characterizing the impact of thermostat setback on market-available dual fuel control systems is noted in the Path Forward section as a future R&D opportunity.

This project's control logic is intended to demonstrate the potential performance advantages of a dual fuel heating system with advanced controls. The control concepts used in the rule set are known to HVAC manufacturers and in some cases are being considered for inclusion in dual fuel system controls, likely with more advanced features (e.g., learning algorithms). The rule set developed and analyzed in this project also had to be straightforward enough to be implemented in the field study (discussed below) through a datalogger-based control system designed by the project team.

Milestone 2.2: Quantification of targeted metrics from performance simulations of multiple configurations, addressing targeted metrics as compared to reference scenario of furnace-only operation.

This milestone was due 7/1/2021 and was completed on 6/20/2021. This milestone required the development of an energy simulation model which integrated the control logic for the dual fuel system (discussed above) and could be utilized to assess the test home's performance using the dual fuel system compared to the baseline home using a furnace-only heating system.

As of June 2021, the project team of Newport and ORNL (modeling lead) had developed an EnergyPlus model of the baseline home (furnace only) and the control home (control-optimized dual fuel heating system) that quantified key metrics for heating system performance, including heating energy consumption, heating energy costs, emissions, heating system runtime, and hours when the heating set point was satisfied (or not satisfied).

The draft control rule set for the dual fuel heating system was coded in Python and imported into the EnergyPlus model. Figures 5 through 7 (below) illustrate the process of developing the EnergyPlus model for the test home (described in Milestone 3.1) and integrating the control logic for the dual fuel heating system. The baseline model was also calibrated using two years of utility billing history.

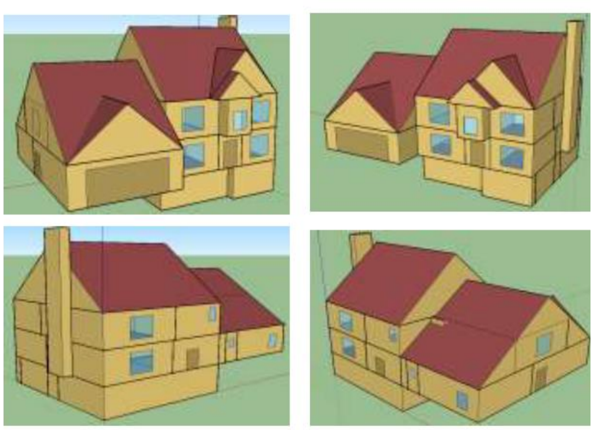

Figure 5 - Building diagram for EnergyPlus model.

Figure 6 - Building plan (top: 2nd floor; bottom: 1st floor).

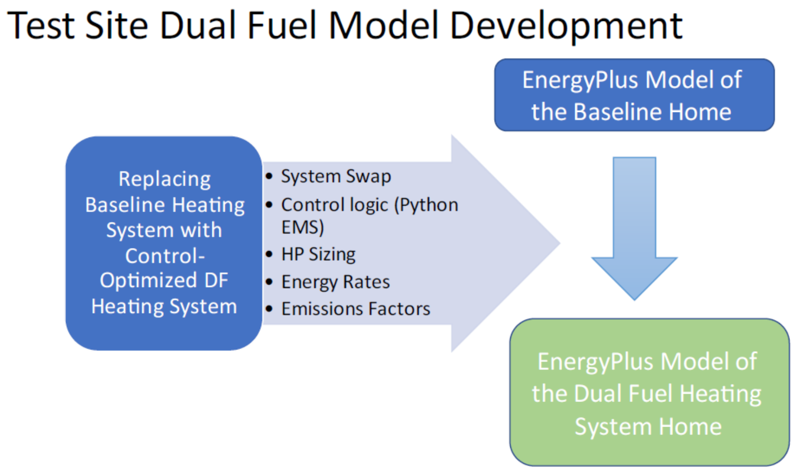

Figure 7 - Overview of updating the baseline energy model (furnace-only) to the dual fuel model with project-developed rule set.

Milestone 2.3: Programmed logic model to be used by the Optimized Heating Control.

This milestone was due on 1/1/2022 and was submitted to DOE by 10/31/2021 as part of the quarterly report. This milestone required the rules described in Milestone 2.1 to be coded into a logic flow and algorithms which could be used in both the energy simulation modeling and the datalogger system deployed in the field study. The logic flow and algorithms are shown in Appendix B. Please refer to the discussion of Milestone 2.1 (above) for a description of the control logic.

Go/No-Go #1: ≥ 35% energy savings for the HHP with the OHC in ≥ 1 configuration vs. a furnace in a cold climate location.

The first Go/No-Go point required the development of energy modeling that demonstrated that the control-optimized dual fuel heating system had heating energy savings of at least 35%, as compared to the furnace-only baseline system. This documentation was due on 7/31/2021 and was submitted on 7/23/2021.

EnergyPlus models of the test site (a typical 2-story existing home in Climate Zone 5) were developed. The baseline model included the furnace-only heating system, and the dual fuel model integrated the control rule set for the dual fuel heating system.

When comparing the heating and fan energy of the dual fuel system (34.17 GJ) to the same end uses for the furnace system (57.79 GJ), there were 40.9% heating energy savings resulting from the control-optimized dual fuel system. This finding validated that the dual fuel heating system operating under the control of the project's rule set would result in significant energy savings over the baseline system.

Milestone 3.1: Cold climate test site recruited, screened, and instrumented with the data acquisition system for the first heating season.

This milestone was due on 7/1/2021 (in advance of the upcoming heating season) and was submitted to DOE on 6/30/2021. Key characteristics of the test site are shown in Figure 8, below. This test site was ideal for several reasons:

- Typical existing home in terms of size and floorplan, in a cold climate (CZ 5)
- Existing forced-air HVAC system included a relatively new, high efficiency furnace and a 20-year-old A/C system at the end of its life cycle
- Home was weatherized such that the heating loads were moderate
    - Heating Load: 52,400 BTU/h
        - Design Ambient Heating Temp: 3° F
    - Cooling Load
        - Total: 23,300 BTU/h
        - Sensible: 20,100 BTU/h
        - Latent: 3,200 BTU/h
        - Design Ambient Cooling Temp: 86° F

Figure 8. Key Characteristics of field test site located in upstate New York.

The home's existing, 96 AFUE gas furnace is shown below in Figure 9. The furnace was located in an unfinished section of the basement which offered adequate space to install the add-on heat pump system in place of the air-conditioning system's A-coil.

Figure 9. The test site's existing high efficiency furnace was installed in 2019.

The complete installation of the datalogger system used to monitor all heating energy inputs, environmental conditions, and system operating metrics took place during the fall of 2021 prior to the winter heating system. Some data monitoring components had lengthy procurement timelines due to COVID-related supply chain issues.

Data was recorded using a CR1000 datalogger from Campbell Scientific. The following sensors were used to feed data to the CR100 datalogger for processing and recording:

- 1x HygroVUE10 measuring outdoor air temperature and relative humidity
- 1x RAD10E solar shield covering the HygroVUE10
- 5x HMP60 measuring air temperature and relative humidity indoors
    - Three of these sensors were distributed among the three floors of conditioned space, including the conditioned portion of a partially finished basement
    - One sensor was installed in the return air duct
    - One sensor was installed in the supply air duct, replaced early in the first heating season with a HygroVUE5 digital sensor due to concerns over temperature range
- 1x HygroVUE5 replaced the HMP60 in the supply duct due to its wider range of safe measurement temperatures
    - A small rose-shaped shield of aluminum foil was used to shield the HygroVUE5 from radiative heating, since it had line-of-sight to both the furnace and heat pump heating coils below.
    - Like the HMP60 it replaced, the HygroVUE5 also measured relative humidity.
- 9x Type T thermocouples in the supply duct (above/below) the HygroVUE5 in a 3x3 array in order to smooth out and average temperature variations across the cross-section of the duct
    - These were also each fitted with a small rose-shaped shield of aluminum foil to shade from radiative heating
- 1x EBTRON EF-A2000-T measuring airflow velocity in return duct
    - A two-sensor unit was required due to the dimensions of the return duct.

- 1x TEC TrueFlow airflow sensor to corroborate airflow measurements from Ebtron sensor above
    - Results from two airflow sensors were found not to match.
- 1x MCS-AC250-TC measuring natural gas flow to the furnace
- 1x RD AMRC-10P-DK-1' collecting pulse output of above gas meter to be sent to datalogger
- 2x each of RWNC-3Y-208-MB Wattnode meter and ACTL-0750-020 current transformer to measure power consumption of blower motor and heat pump compressor
- 1x CS320-50-PT thermopile pyranometer for measuring outdoor solar irradiance

Measurements of each variable were taken by the datalogger every 5 seconds and averaged or accumulated over 60-second, 60-minute, and 24-hour intervals. One data file was continuously generated at each of these three intervals. Software applications LoggerPro, PC400, and occasionally LoggerLink (Android) were used to establish and edit the data measurement program and to monitor and retrieve data files.

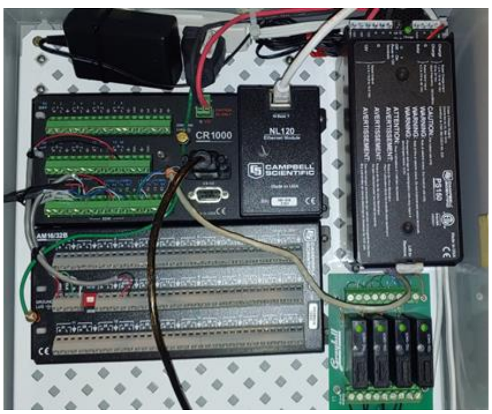

Figure 10 (left). CR1000 datalogger (black with green rails), multiplexer (black with grey rails), power supply, and relays for system outputs (lower right).
Figure 11 (right). Temperature sensors inside the supply plenum before foil radiation shields were added. Nine thermocouples are mounted in 3 rows and a digital temperature and relative humidity sensor is mounted above the thermocouples in a copper conduit.

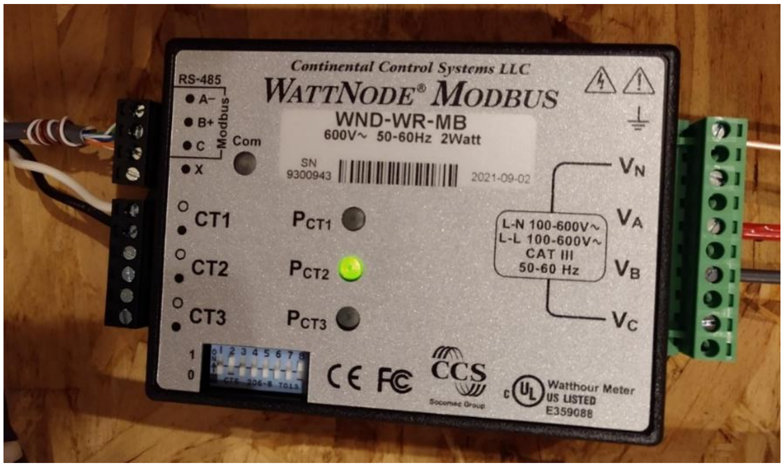

Figure 12. WattNode device used to measure electrical energy consumption of heating system loads including the central blower and the heat pump compressor. A gas submeter was installed to record furnace gas consumption.

Milestone 3.2: Data analysis from first heating season, including heating equipment time of use, site energy use (and associated source energy use estimate), emissions estimate, and climatic data.

The summary of the Winter 1 heating season data (2021-2022 winter) was due on June 1, 2022. The project team submitted this deliverable to DOE on June 1, 2022. The primary objective of this phase of the project was to establish the baseline energy performance of the home under heating conditions. This baseline then served as the basis for comparing and assessing the control-optimized dual fuel heating system during Winter 2 (2022-2023).

Some highlights of the Winter 1 data analysis include:

- A strong relationship between heating energy consumption and indoor-outdoor Delta T.
- A detailed analysis on a very cold day (colder than design temperature) showed heating loads much lower than the initially modeled design heating load. This information was subsequently factored into the heat pump sizing.
- Established the analysis methodology to assess indoor temperature deviation from thermostat set point.

The analysis of Winter 2 heating season performance data (Milestone 3.4) includes direct comparisons with the same metrics from Winter 1. To reduce redundancy, Winter 1 data analysis is presented alongside the Winter 2 analysis in the Milestone 3.4 summary below.

Milestone 3.3: Dual Fuel Heat Pump with optimized controls is installed and commissioned with the data acquisition system (DAS) for the second heating season.

This milestone represented the selection, procurement, and installation of the add-on heat pump at the test site along with the hardware and programming necessary to implement the control rule set. This milestone was due on September 15, 2022. The heat pump was selected and specified by this time, with the actual installation occurring in October 2022. Installation required additional time because of delays in procuring all components of the heat pump system and downstream delays in scheduling the installation with the selected contractor.

Prior to procuring and installing the heat pump, the project team first assessed the home's design heating and cooling loads compared to available heat pumps suitable for this retrofit application. Single speed heat pumps were not sufficient because their similar heating and cooling capacities were not well matched to the home's loads (52.4kBtu/hr. for heating and 23.3 kBtu/hr. for cooling). A single speed heat pump would have been very undersized for the heating load (if sized for cooling), resulting in very little heat pump operation for space heating. Or conversely, if sized for heating, the heat pump would be grossly oversized for cooling resulting in short cycling, poor latent moisture removal, and potential comfort issues.

Two-speed heat pump systems capable of dual fuel integration were also assessed. However, these units generally did not have enough difference between stage 1 and stage 2 capacity levels to align with the home's loads. If a two-speed heat pump had been sized to align the stage 2 heating output to align with the home's design heating load (or most of it), the unit's lower stage 1 capacity would still have been much higher than the design cooling load.

A heat pump with a variable speed compressor was selected as the most appropriate system, with a maximum heating capacity of 48,000 BTU/h and a minimum cooling capacity of 16,000 BTU/h. This system was a Mitsubishi IntelliHeat heat pump system which is intended to be retrofit in tandem with an existing furnace to create a dual fuel heating system. This heat pump was controlled via a combination of its own native controls and the study's smart control algorithm (implemented through the programmed datalogger).

The added step of establishing a method to override some of the native controls of the heat pump required additional coordination time with the project team and control engineers from Mitsubishi. The final approach involved installing an interface "dongle" supplied by Mitsubishi which could toggle the dual fuel system between furnace and heat pump selection, based upon the control rules programmed into a Campbell Scientific datalogger and its low voltage output channels (which was part of the data acquisition system described above under Milestone 3.1). Pictures of various components are shown below.

Figure 13 - Furnace and blower cabinet with new heat pump coil installed above. The available vertical space to install this coil in place of the old cooling coil was assessed as part of the system selection.

Figure 14 - Dongle that allowed the project's control logic to be implemented on the test site's dual fuel heating system

Go / No-Go #2. Demonstrate savings for the control-optimized heat pump of at least 35% versus the reference case of a fossil-fuel fired furnace, based on analysis conducted with an energy simulation model that has been calibrated with the test site's field monitoring from Winter #1.

Documentation of this decision point was due on September 1, 2022, and was submitted to DOE on July 12, 2022. This deliverable focused on the model calibration process (Figure 15) and included data illustrating the modeled outputs for the building simulation as compared to actual, monitored values from Winter 1 (examples shown in Figures 16 – 17). Based on this calibrated model, the team evaluated the energy savings impact of a dual fuel system implementing the control logic described in

Milestone 2.1. Annual heating energy savings for the dual fuel system as compared to the furnace-only baseline system were 37.4%, as shown below in Figure 18.

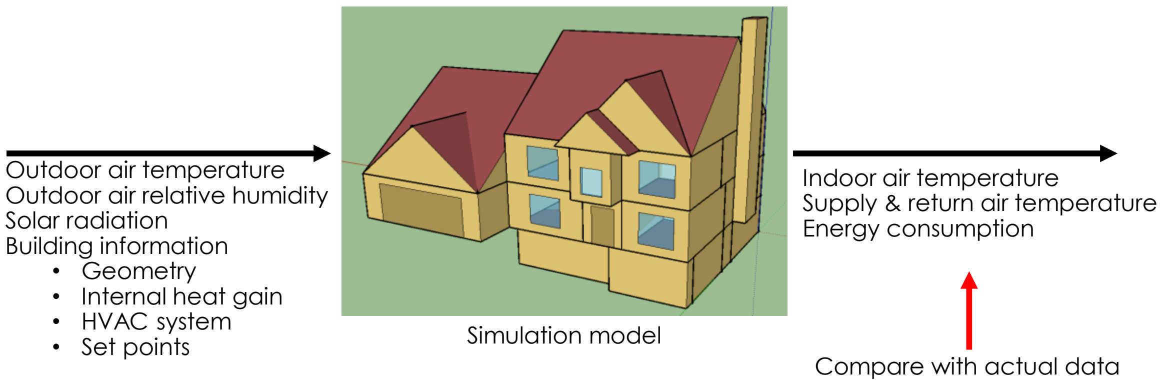

Figure 15. Calibration process.

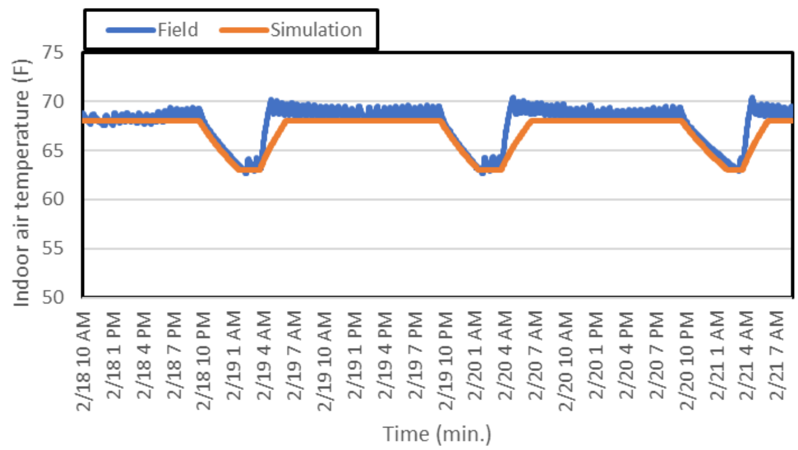

Figure 16. Indoor (first floor living room) temperature, field measurements vs. simulation.

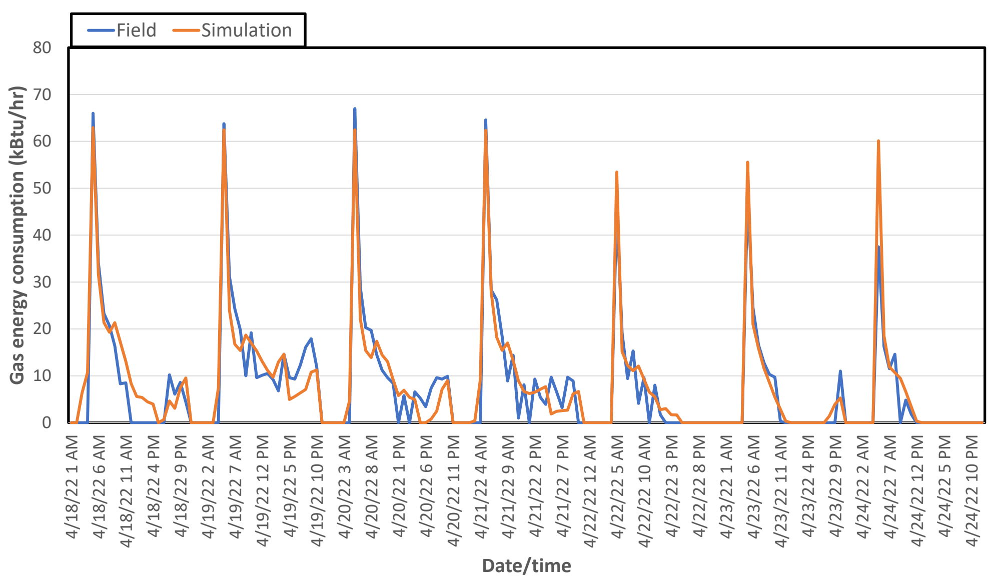

Figure 17. Furnace gas consumption, field measurements vs. simulation.

Annual Heating Energy Savings Analysis

	Electricity (kBtu/year)	Gas (kBtu/year)
Heating + Fan	4,846	55,863
Total	60,708	

Annual heating energy consumption of the base (furnace-only) model

	Electricity (kBtu/year)	Gas (kBtu/year)
Heating +Fan	11,867	26,111
Total	37,978	

Annual heating energy consumption of the proposed (dual fuel heating) model

Heating Energy Savings : (60,708-37,978)/60,708= **37.4%**

Figure 18. Annual heating energy analysis shows 37.4% savings from control-optimized dual fuel system.

Milestone 3.4: Data analysis from second heating season, including heating equipment time of use, site energy use (and associated source energy use estimate), emissions estimate, and climatic data.

This milestone represented a parallel analysis to the Winter 1 analysis (Milestone 3.2) and provided a detailed performance comparison between the control-optimized dual fuel heating system and the baseline (furnace-only) system at the test site. Milestone 3.4 was due on June 1, 2023, following Winter 2, and was submitted to DOE on June 1, 2023.

Major conclusions from the Winter 2 analysis and comparison to Winter 1 heating system performance include the following:

- Field data demonstrated significant energy use, energy cost, and emissions savings are possible when deploying control-optimized dual fuel heating system in a TOU electric rate environment. See Figure 19 below.
- Implementation and impact of the control scheme is dependent on energy rates and efficiency levels of both the heat pump and the furnace.
- Integration of thermostat setback can potentially have unanticipated impacts on how a dual fuel heating system will perform and should be carefully considered. For this reason, a thermostat setback was not included in this final study design.
- No major resident comfort issues or interior temperature deviations were noted with the use of the control-optimized dual fuel heating system.

Appendix C contains numerous graphs from the Winter 1 and Winter 2 analyses that support these conclusions.

	Winter 1 (Furnace)	Winter 2 (Dual Fuel w/ Optimized Controls)	Percent Reduction
Normalized Heating Energy Use	9.94 kBTU/HDD	4.69 kBTU/HDD	52.8%
Normalized Heating Energy Cost	\$0.110/HDD	\$0.092/HDD	16.4%
Normalized CO2 Emissions from Heating	1.25 lbs./HDD	1.03 lbs./HDD	17.8%

Figure 19. Comparison of heating system performance metrics.

Milestone 4.0: Outline of scaled-up modeling to identify scope and metrics.

This milestone required the development and final selection of the scaled-up modeling scope to define what this task would cover. Milestone 4.0 was due on September 30, 2023.

The project team initially developed a draft of the scaled-up modeling scope to gain feedback from the project Advisory Group and DOE. Potential system design variables (i.e., heat pump capacity) were considered as possible issues to explore further with broader modeling. The relative importance of analyzing different variables was also discussed with the Advisory Group, particularly utility sector members. For example, the implications of building tightness were seen as an important variable to understand because utilities could impact this variable through weatherization implemented in tandem with a dual fuel retrofit.

The team finalized the scope of the scaled-up modeling task and submitted this to DOE on September 30, 2023. The variables selected for analysis in the modeling study were:

- Control Rule Set: assess system performance metrics as a function of the control method used to operate the dual fuel heating system.
- Heat Pump Heating Capacity: assess overall system performance as a function of different heat pump capacity levels relative to the design heating load.
- Electric Rates: compare overall system performance as a function of the Time of Use electric rates or the use of static electric rates.
- Building Tightness Level: assess system performance for a leaky building envelope as compared to a well air-sealed building envelope.
- Emissions Factors: compare system performance as a function of the emissions factors used for electricity consumption.

Additional detail on these modeling variables is provided in the next milestone description. Modeling locations in Climate Zones 4, 5, and 6 were selected to characterize system performance across these variables in mixed and cold climates. These modeling locations were selected because dual fuel systems offer the potential to introduce cost-effective electric heating to satisfy a portion of the load in these regions. DOE's standard residential prototype building model was used for this analysis.

Milestone 4.1: Normalized, climate-specific results from building energy simulations identifying performance of control-optimized dual fuel heating system versus the reference case.

This milestone incorporated the modeling results generated from extensive EnergyPlus simulations across the variables described in Milestone 4.0, with a due date of March 31, 2024. The project team presented the key findings from the Scaled-Up Modeling Analysis to DOE during the quarterly check-in call on April 26, 2024. Based on discussions following this presentation, the team refined and submitted the final modeling findings in early May 2024.

The specific modeling scenarios are depicted below in Figure 20. The default setting for a given variable (Column 2) was applied when a different variable was being modeled. For example, when modeling different building tightness levels, the control rule set was assumed to be the dynamic rule set based on lower cost per BTU instead of a switchover temperature.

Scenarios

	Default setting	Variations to Explore in Modeling	Variations	# of scenarios
Control rule set	Dynamic control ruleset used in field evaluation	Compare a basic switchover temp rule to the rule set used in the project	20F and 40F vs. Dynamic control rule set (baseline)	3 (scenario) x 3 (climate zone)= 9
Heat pump heating capacity	ASHP, variable speed system sized to meet most of home's design heating load	Set an HP capacity that can handle less than baseline case	Target levels of 60%, 80%, and 100% (baseline). Actual percentage varies based on climate zone	3 (scenario) x 3 (climate zone)= 9
Electricity rates	Use the Time of Use rate schedule currently in place for the dual fuel modeling	Static electricity price	Time of Use rate schedule (baseline) vs. static	2 (scenario) x 3 (climate zone)= 6
Building Tightness Level	Infiltration value that is assumed in the DOE prototype home models	A leakier home that has 2x the leakage level of the prototype home model.	1x (baseline) and 2x the leakage level (infiltration value)	2 (scenario) x 3 (climate zone)= 6
Emission factors	Static national averages were used from EPA emissions calculator	Regional emission rate from EPA eGRID.-	baseline vs. Regional emission rate	2 (scenario) x 3 (climate zone)= 6

Figure 20. Modeling scenarios and variable definitions.

A building simulation model calibrated with the field data was used for both the reference model (furnace-only heating system) and the dual fuel heating system model. The ORNL team used outdoor conditions, indoor air temperature, and system energy consumption to calibrate the simulation model.

The specific locations representing climate zones 4, 5, and 6 were:

- New York, NY (CZ 4A – mixed humid)
- Denver, CO (CZ 5B – cool dry)
- Rochester, MN (CZ 6A – cold humid)

Design characteristics of the calibrated simulation model include the following:

- Single family detached home on basement foundation
- Energy features based on 2006 IECC (e.g., wall R values, window specs)
- Weather file was the TMY3 weather file incorporated in EnergyPlus
- Baseline infiltration at 0.35 Air Changes per Hour (ACH)
- Heat pump system type (cold climate heat pump inputs including performance curves)
- Heat pump system sizing – baseline size met most/all of home's heating load at design conditions. Figure 21 (below) shows additional detail on the heating system sizing and loads.

Climate zone	Heating Load at Design Temp (Btu)	Gas Furnace Capacity (Btu)	Heat Pump Capacity (Btu)			
			Stage 1	Stage 2	Capacity at 5F	Heat Pump Capacity at 99% Design Temp
CZ 4	26,949	30,000	24,000	48,000	27,082	30,461 (-10.7°C; 12.74°F)
CZ 5	31,191	36,000	27,000	54,000	30,467	28,094 (-17.9°C; -0.22°F)
CZ 6	40,977	42,000	36,000	72,000	40,622	29,545 (-26.2°C; -15.16°F)

Figure 21. Heating system capacity and design heating loads.

Another important feature of the modeling analysis was the electric rate structure used to estimate heating energy costs associated with electricity consumption. A Time of Use (TOU) rate structure was implemented as the default assumption to demonstrate the ability of the control logic to take advantage of changing electric prices. To develop the TOU rates, the project team first compiled residential TOU electric rates from a sample of U.S. utilities in mixed and cold climates during the 2024 heating season. Three-tier rate schedules were chosen as a focus over two-tier schedules, which would accentuate the ability of the dual fuel system's control logic to dynamically respond to different prices. Ratios of the three tiers were determined for each utility (e.g., highest tier to middle tier ratio). Then these ratios were averaged across the different utilities to arrive at a set of "standard" ratios for a three-tier TOU rate schedule. The ratios were applied to a 2022 national average electric rate of $0.1512/kWh to produce the TOU schedule shown below in Figure 22 (DeVilbiss, 2023).

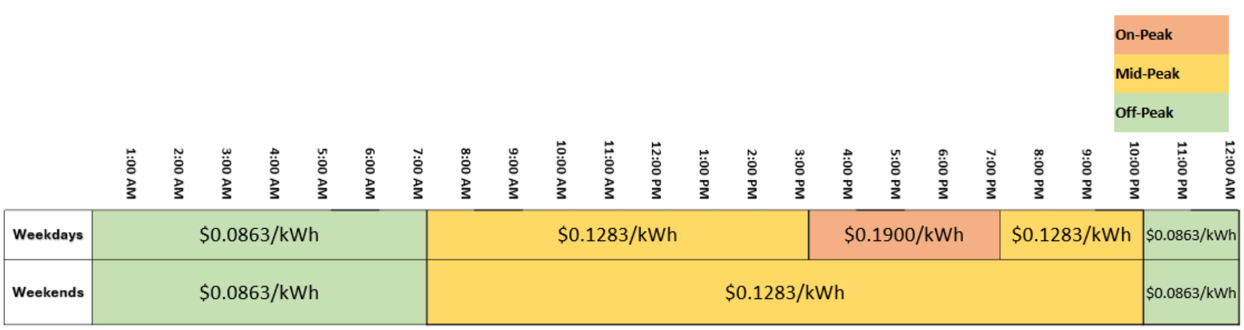

Figure 22. Three-tier TOU electric rates applied as default in energy modeling.

The most salient findings from the modeling analysis are presented and described in the Utility Fact Sheet (see Appendix D), a deliverable under Milestone 5.1. The Utility Fact

Sheet drew most of its findings and recommendations from the most prominent results of the modeling analysis completed under this task (4.1). The Fact Sheet targets a utility industry audience and provides insights on key deployment issues for add-on heat pump retrofit applications. For example, the fact sheet illustrates the implications of different heat pump capacity levels in terms of heating energy costs, and site energy use across climate zones 4 – 6.

Milestone 5.1: Utility guidance document for establishing minimum functionality and feature specifications for control-optimized dual fuel heating systems, also including information on criteria for appropriate homes.

This deliverable summarized the most significant project findings with a focus on the modeling-based results that can be leveraged by utility energy efficiency programs to inform dual fuel retrofit implementation. This deliverable was due on July 31, 2024 and was submitted to DOE on June 27, 2024 in draft format. A final version of the Utility Fact Sheet incorporating edits and comments from several stakeholders including utility sector members of the Advisory Group was submitted August 21, 2024. This 5-page document includes numerous graphics to relate the energy and emissions impacts of different design variables for dual fuel heating system retrofits. The fact sheet is included in Appendix D.

Milestone 5.2: Conference presentation or webinar for utilities, efficiency organizations, and regulators summarizing final results.

This presentation milestone involved summarizing the key project findings that can be used by utilities and their implementation contractors to inform dual fuel heating system retrofits for existing homes. The milestone was due on June 30, 2024. The project team focused on presenting at the Association of Energy Service Professionals (AESP) Summer Con 2024 as this event convenes utilities, efficiency consultants that design and implement utility programs, and other related organizations. The proposal submission to present was accepted in April 2024 and the team presented on July 24, 2024. The presentation was well-received, and attendees showed significant interest in dual fuel heating system retrofits. Project staff also met a few utilities that are currently implementing dual fuel retrofit programs. A copy of this presentation may be found in Appendix E.

End of Project Goal: Final report demonstrating full-season normalized energy savings of 45% vs. a furnace and ≤ 3% of heating season hours with > 3° F deviation between t-stat set point and room air temperature.

Each of the metrics noted in this goal were embedded in the full Winter 1 – Winter 2 energy analysis and comparison (Milestone 3.4). Figure 19 above documents normalized energy savings of 52.8% for the control-optimized dual fuel system compared to the baseline furnace system. The final graph in Appendix C illustrates that there were no hours at the field site when the indoor air temperature was off by 3° F or more from the thermostat setpoint. The homeowner also did not report any comfort issues during Winter 2. These findings were submitted as part of Milestone 3.4 (June 1, 2023) and were repeated in the 2024 Q3 quarterly report.

Significant Accomplishments and Conclusions

This work is highly valuable because it demonstrates the energy, cost, and emissions reductions that resulted from a field-deployed, control-optimized dual fuel heating system in a cold climate U.S. home. Significant additional value was gained by leveraging the field study to create calibrated simulation models (baseline home and dual fuel home) which were used to conduct a broader and deeper analysis. This modeling analysis provides valuable insights on the system performance implications resulting from different control methods, heat pump capacities, building tightness levels, and electric rate structures.

This research also harmonizes with related technology and policy trends in the industry by evaluating heat pumps with the ability to meet most or all of the home's design heating load and integrating Time of Use electric pricing in the analysis. Furthermore, "add-on" heat pumps are increasingly available in the market from manufacturers including Mitsubishi, Gree, and Bosch.

While the availability of residential TOU electric rates appears to be growing, the logic used in this project to select the more economical heating source (furnace or heat pump) by integrating with TOU rate schedules is not currently available in DF system controls on the market. The project team anticipates that control options similar to the logic developed in this project will become increasingly available in the market. This challenge is also mitigated to some extent by project findings that demonstrate significant energy, cost, and emissions benefits from simply using a dual fuel system with a 20° F switchover temperature as compared to a furnace-only system (see Appendices D and E). Ideally, availability of smart controls for dual fuel heating systems that account for TOU rates will improve soon, and in the meantime, high-capacity heat pumps in dual fuel systems with much lower switchover temperatures can yield meaningful benefits over furnace-only systems.

This project raises awareness of dual fuel retrofit systems and their potential benefits. The Utility Fact Sheet (Milestone 5.1) along with the conference briefing at AESP (Milestone 5.2) are key resources for sharing the project findings and have been disseminated with utilities, industry groups focused on efficiency, and DOE national labs, HVAC manufacturers, the ENERGY STAR Thermostat program, the ENERGY STAR NextGen program, and other stakeholder groups.

Overall, this study provides analysis-based estimates for the increase in performance that may be achieved when dual fuel systems are retrofitted to augment a furnace-only heating system. This work comes at a time when utility programs are focused on introducing cost-effective electric space heating for U.S. homes. This project's field study, combined with subsequent modeling analysis focused on dual fuel heating systems with innovative controls, provides unique insights into this retrofit technology.

Path Forward

As described in the Background section, there are several issues involved in scaling up the deployment of dual fuel heating system retrofits in U.S. homes. This translates to a multi-faceted path forward.

The Newport and Oak Ridge team does not currently have specific follow-up research work related to this project. However, both organizations will continue to integrate the findings from this research into other related programs including training, energy modeling development, and above-code program management. The project team is also conducting tech transfer to share project background and findings with the following groups:

- Consortium for Energy Efficiency's Emerging Technology program
- DOE Building Energy Codes program
- EPA ENERGY STAR Thermostats program
- EPA NextGen program
- NREL's Heat Pump Modeling R&D program
- American Council for an Energy Efficient Economy (ACEEE)

Additional R&D opportunities to advance this technology and accelerate energy use reductions, cost savings, and fuel flexibility include the following:

- Conducting a pilot study on dual fuel systems with grid-interactive controls that can respond in real time to utility pricing or other signals to promote grid management and stability. This work would assess price implications, consumer perceptions on comfort, and grid management benefits.
- Conducting a market survey of utility programs that incentivize dual fuel retrofits. This research would illustrate and assess program characteristics, requirements related to heat pump controls and sizing, requirements related to weatherization, program participation, and any program policies related to electric rate structures.
- Conducting research focused on current dual fuel system controls in the market and how they interact with thermostat setbacks. Based on these findings, develop industry guidance on the use of setbacks and update energy modeling tools.

Products

Lead by ORNL staff, we wrote the paper titled *Potential Heating Energy and Cost Savings of Dual Fuel Heat Pump Control as a Retrofitting Method for Residential Buildings in the U.S.* This paper was also presented at the 2022 Building Performance Analysis Conference in September 2022.

Project Team and Roles

Newport Partners was the prime contractor responsible for research design, control logic development, field demonstration, publication development, and project management and reporting. Oak Ridge National Lab (ORNL) lead energy simulation analyses and supported datalogger programming and configuration for the field assessment. The project Advisory Group was comprised of manufacturers, utilities, and energy efficiency organizations and provided feedback and direction the research design and findings.

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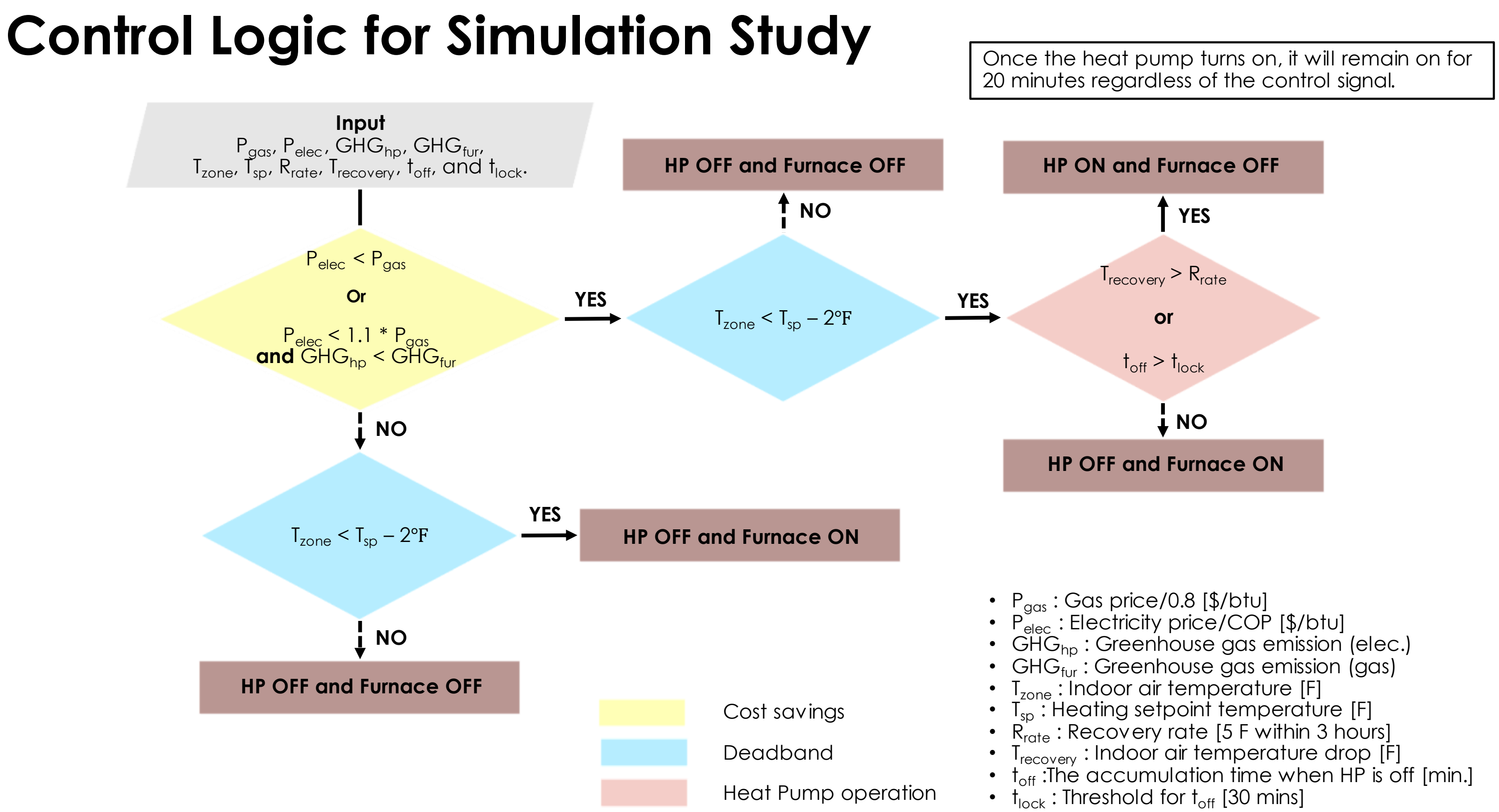
Appendix A: Advisory Group Composition

The following organizations had representatives participating in the project Advisory Group as of 12/2020. The group's roster included some additions during the project period as well.

Organization	Title	Sector
Air-Conditioning, Heating, and Refrigeration Institute	Vice President, Research	HVAC Manuf.
Consortium for Energy Efficiency	Senior Program Manager	Efficiency Org.
Ecobee	Partnership Manager	HVAC Manuf
Eversource	Program Manager – Emerging Technologies, Energy Efficiency	Utility
Google Nest	Senior Building Scientist	HVAC Manuf.
Johnson Controls	Executive Director for Advanced Technology	HVAC Manuf.
Johnson Controls	Director of Regulatory and Environmental Affairs	HVAC Manuf
Massachusetts Clean Energy Center	Director, Clean Heating & Cooling	Efficiency Org.
Mitsubishi	Director, Product Management - Residential	HVAC Manuf.
Mitsubishi	Performance Construction Technical Lead	HVAC Manuf
Nationalgrid	Manager, NYS My Energy Solutions Residential Program Operations	Utility
Northeast Energy Efficiency Partnerships (NEEP)	Director, Technology and Market Solutions	Efficiency Org.
Northwest Energy Efficiency Alliance (NEEA)	Senior Product Manager	Efficiency Org.
ORNL	Building Technologies and Research Integration Center	
Resideo Connected Homes	Sr. Manager, Business Development	HVAC Manuf.
Resideo Connected Homes	Marketing Program Manager	HVAC Manuf
Rheem	Engineering Manager, R&D Systems; Residential Air Conditioning	HVAC Manuf.
Southern Company	Research Engineer, Intelligent Buildings Research	Utility
Rheem	Engineering Manager, R&D Systems; Residential Air Conditioning	HVAC Manuf.
Xcel Energy	Sr. Energy Efficiency Engineer	Utility

Appendix B: Control Logic Flow Chart



Appendix C: Summary of Winter 1 and 2 Field Site Energy Analyses

List of Variables Measured

Temperatures

- Indoor Temperatures & Relative Humidity
  - First Floor (At thermostat)
  - Second floor
  - Basement
  - Supply plenum
  - Return plenum
  - Two supply registers
- Outdoor Temperature & Relative Humidity
- Thermocouple array for redundant supply temperature measurement

Other

- Time stamp of each measurement
- Battery Voltage, Panel Temperature
- Airflow through central air handler
- Furnace natural gas consumption
- Central air handler electric consumption
- Heat pump compressor electric consumption
- Solar irradiance on property

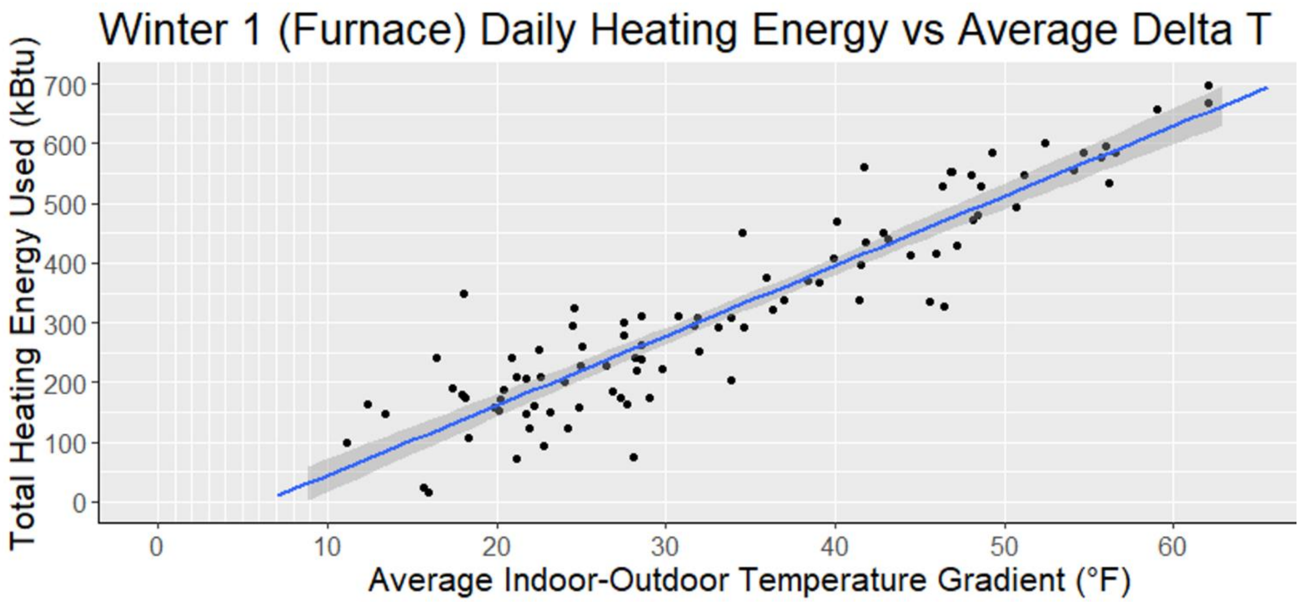
Other Variables

Assigned

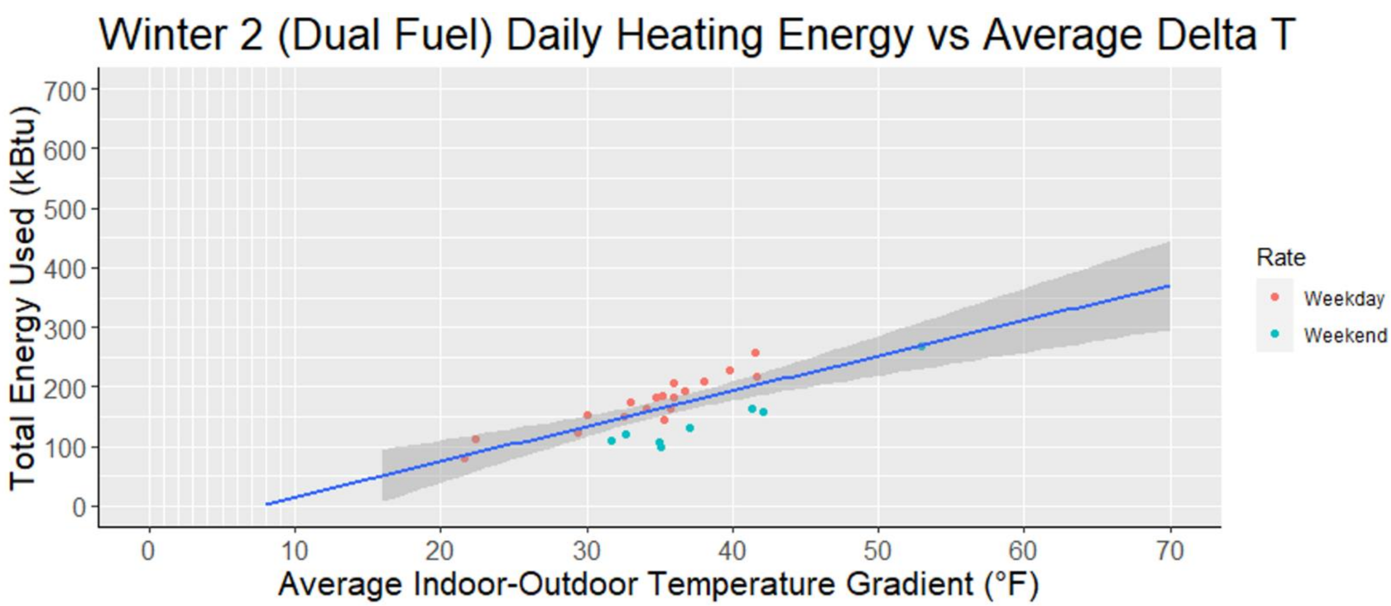
- Natural gas price per therm (constant)
- Natural gas GHG emissions per therm
- Furnace efficiency
- Electric price per kWh (time of use)
- Electric GHG emissions per kWh

Calculated

- Heat pump COP based on outdoor temperature
- Price per BTU heat delivered from each heating system
- Electric GHG emissions per BTU heat delivered
- Gas GHG emissions per BTU of heat delivered

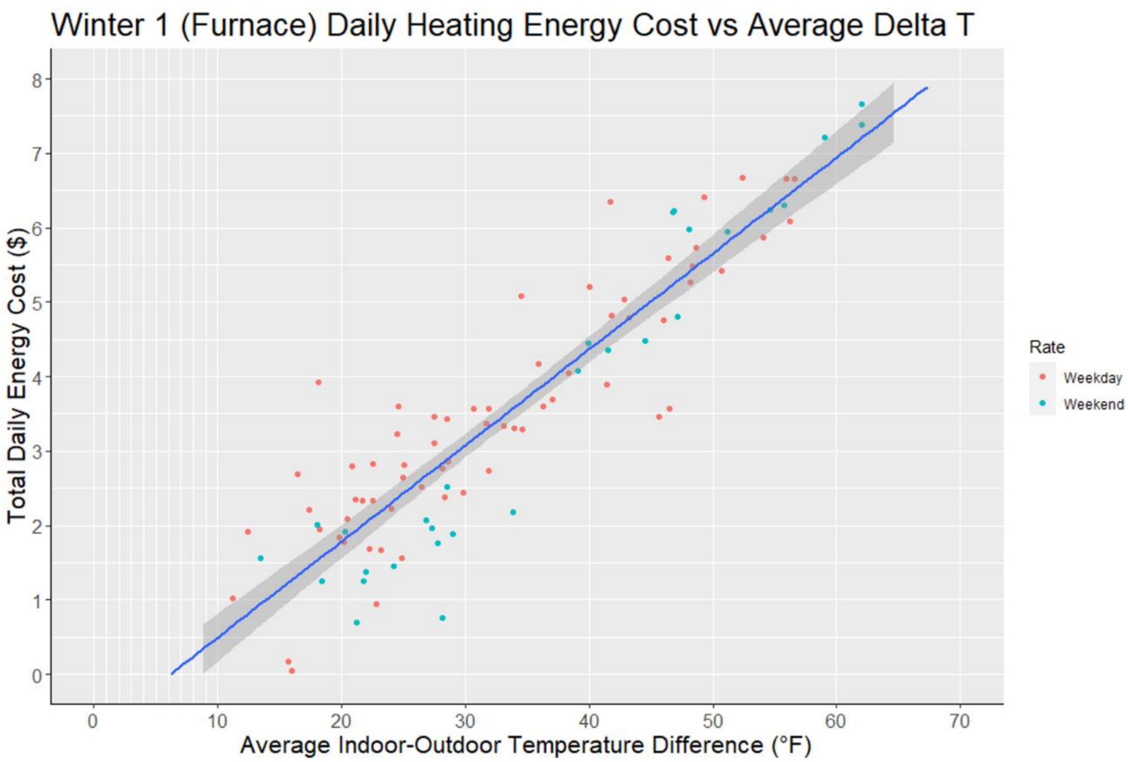


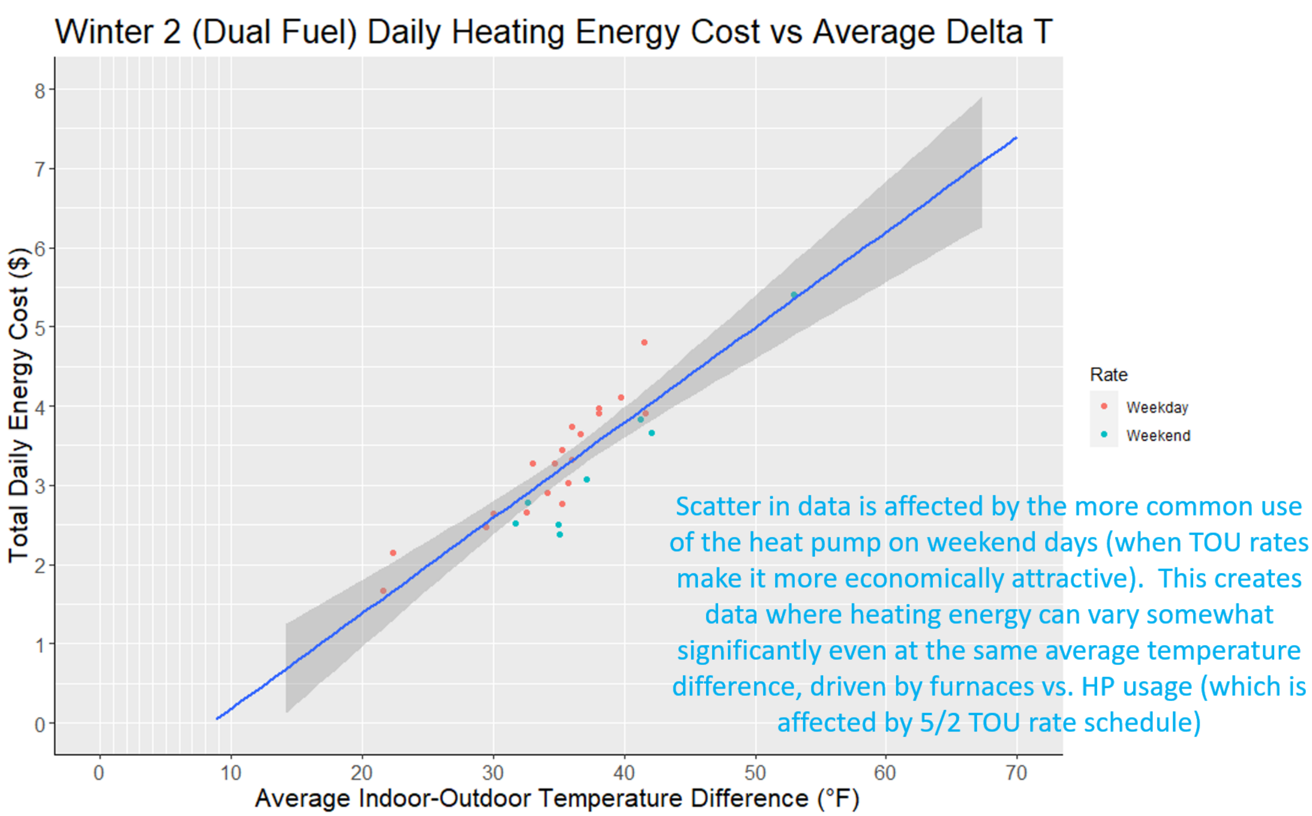
Line of best fit: y = 10.55*x – 30.29
Zero load point: 2.9°F
Adjusted R-Squared: **0.80**
Each point is one day

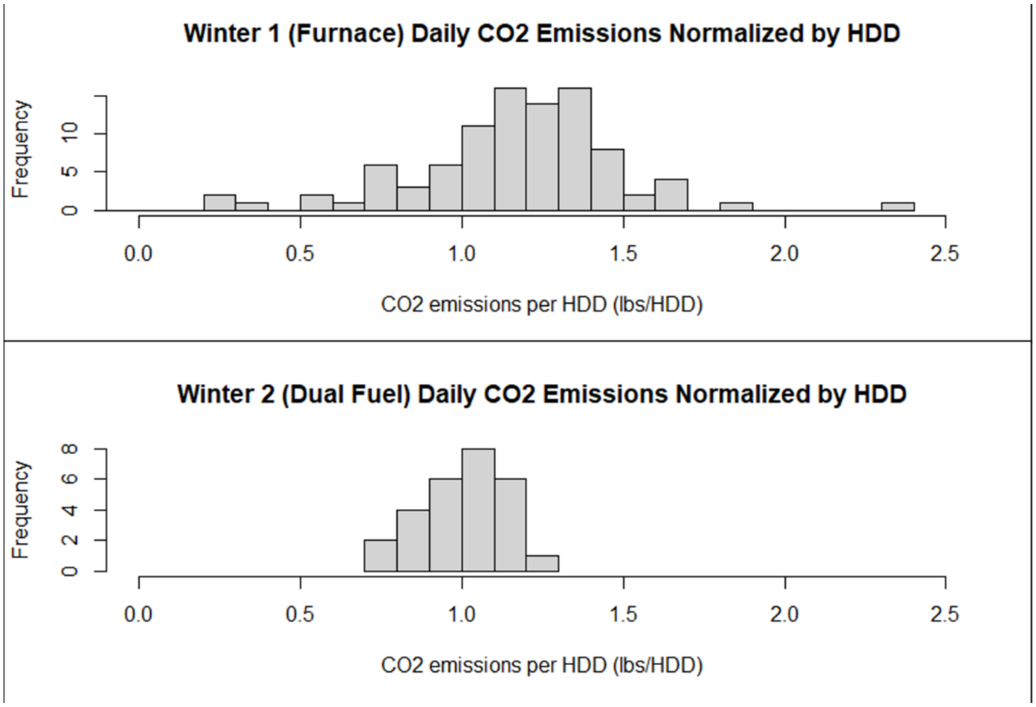


Line of best fit: y = 5.92*x – 43.69
Zero load point: 7.4°F
Adjusted R-Squared: **0.55**
Each point is one day

Scatter in data is affected by the more common use of the heat pump on weekend days (when TOU rates make it more economically attractive). This creates data where heating energy can vary somewhat significantly even at the same average temperature difference.


Winter 1 (Furnace) Daily Heating Energy Cost vs Average Delta T
Total Daily Energy Cost ($)
Average Indoor-Outdoor Temperature Difference (°F)
Rate
Weekday
Weekend


Winter 2 (Dual Fuel) Daily Heating Energy Cost vs Average Delta T
Total Daily Energy Cost ($)
Average Indoor-Outdoor Temperature Difference (°F)
Rate
Weekday
Weekend
Scatter in data is affected by the more common use of the heat pump on weekend days (when TOU rates make it more economically attractive). This creates data where heating energy can vary somewhat significantly even at the same average temperature difference, driven by furnaces vs. HP usage (which is affected by 5/2 TOU rate schedule)



Emissions factors, same as those used in control algorithm, are national averages sourced from [EPA Greenhouse Gas Equivalencies Calculator]

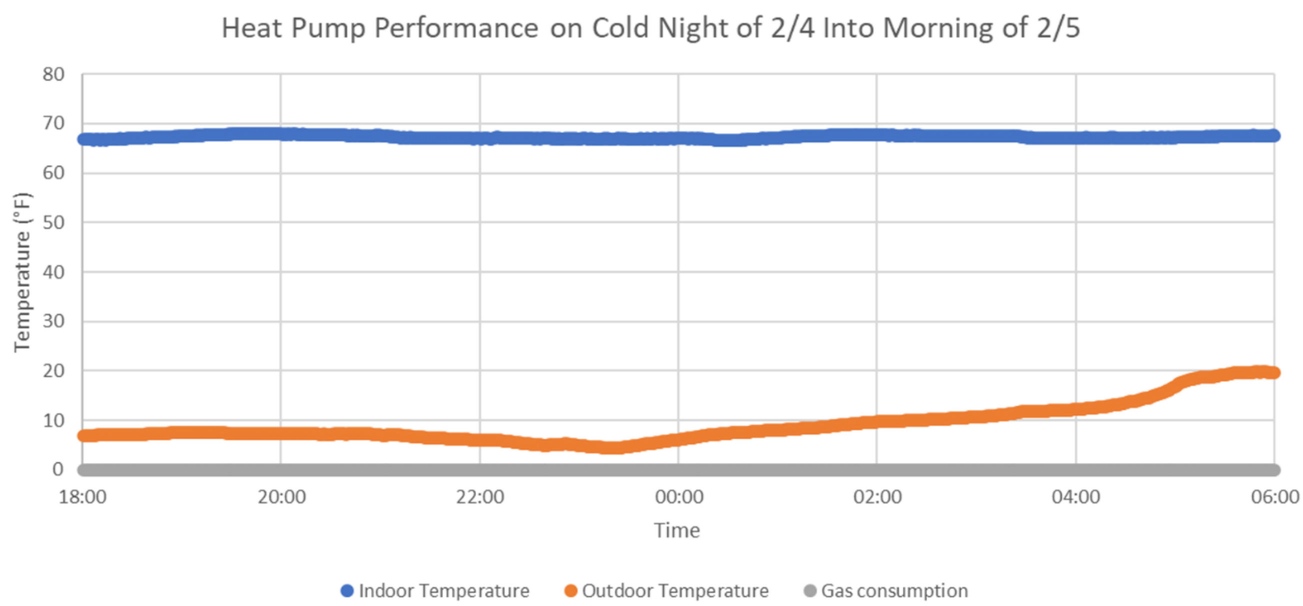
Comparison of Major Metrics

	Winter 1 (Furnace)	Winter 2 (Dual Fuel w/ Optimized Controls)	Percent Reduction
Normalized Heating Energy Use	9.94 kBTU/HDD	4.69 kBTU/HDD	52.8%
Normalized Heating Energy Cost	$0.110/HDD	$0.092/HDD	16.4%
Normalized CO2 Emissions from Heating	1.25 lbs./HDD	1.03 lbs./HDD	17.8%

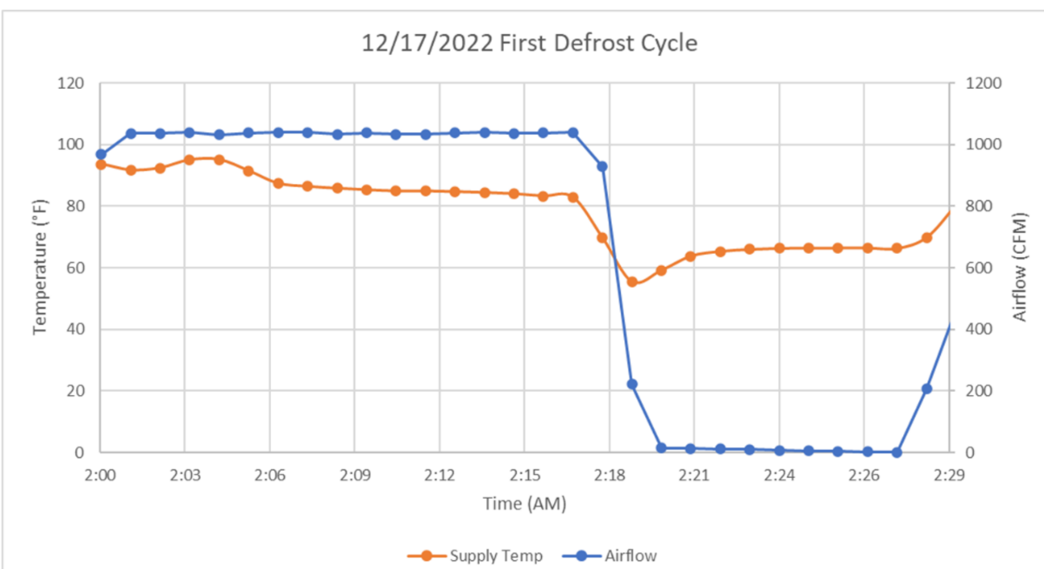
Analyses and Characterizations of Dual Fuel Heating System Operations

Example of Near-Design Temp Heat Pump Performance

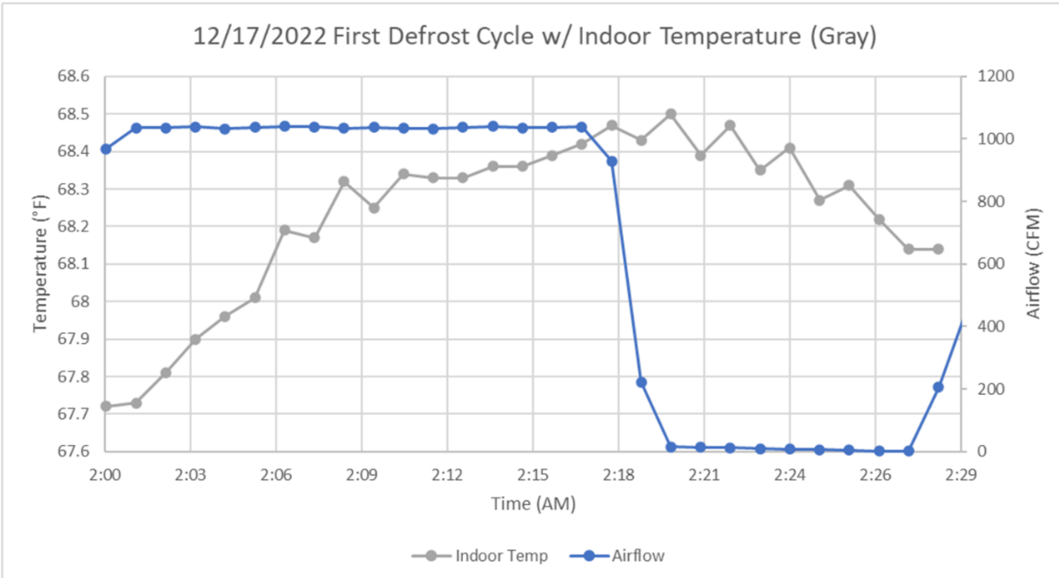
No gas consumption, single-digit temperatures most of the night

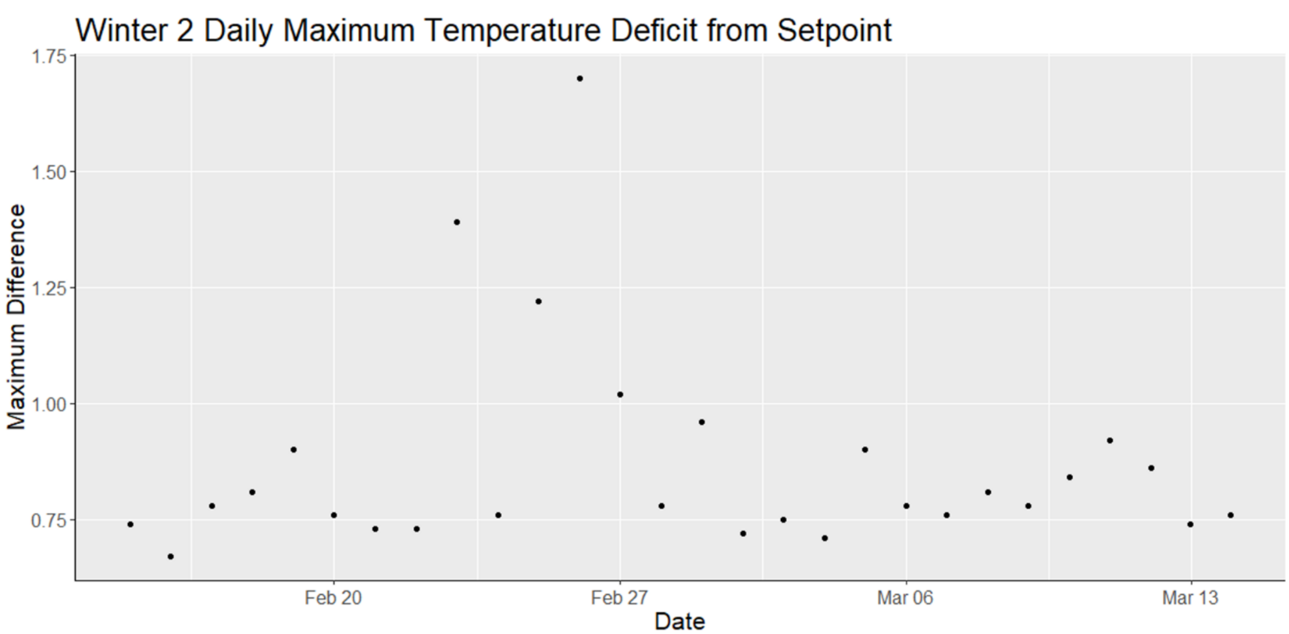


Verification that Central Blower Operation Stops during a Defrost Cycle



Indication that Indoor Temperature is not Significantly Impacted by Defrost Cycle





Zero hours with 3°F or greater deviation between thermostat set point and room air temperature.
Set point for this heating season was constant at 68°F.

Appendix D: Utility Fact Sheet

Dual Fuel Heating System Retrofits with Advanced Controls

An energy, carbon, and cost-saving opportunity for gas-heated homes

This material is based upon work supported by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under the Building Technologies Office, Award Number DE-EE0009076. The views expressed herein do not necessarily represent the views of the U.S. Department of Energy or the United States Government.

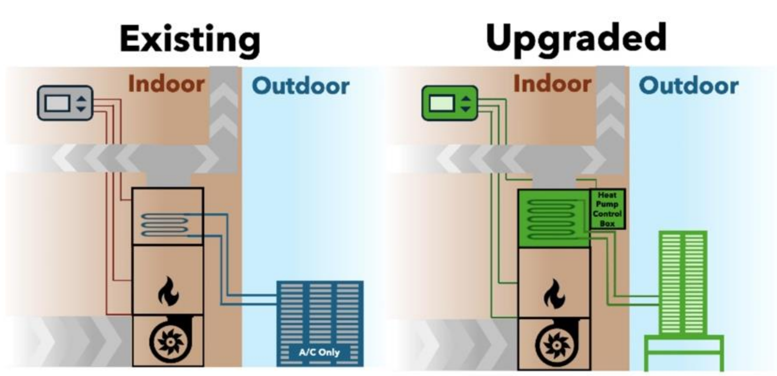
There are roughly 38.5 million homes in the mixed and cold climate regions of the U.S. (about 48% of the housing stock) with a gas based forced-air heating system. As utilities and energy efficiency programs seek to reduce energy use, GHG emissions, and costs, these homes are candidates for an **add-on heat pump with advanced controls**. This technology offers the potential for retrofits to reduce energy, costs, and carbon while keeping residents comfortable.

38.5 million applicable housing units in IECC Climate Zones 4-6

Technology Overview

Dual Fuel Heating	Retrofit	Control-Optimized
Heating a home with both a **gas-fired** furnace and an **electric** heat pump with the capacity to provide adequate heating under most or all outdoor temperatures.	Replacing an existing air conditioner with a heat pump that cools in the summer and provides heating in the winter.	Using advanced controls that consider both **energy cost** and **system efficiency** to determine which system (furnace or heat pump) to use at different times.

This study investigated a home where an old A/C unit was replaced with a variable capacity heat pump system (indoor coil, outdoor unit, and controls). The heat pump system was added to an existing, relatively new forced-air furnace and utilized the furnace's blower and duct work. Additional hardware was used to implement customized advanced controls, which selected the furnace or heat pump based on the lower energy cost per BTU. The control logic also included rules to ensure that indoor temperature levels were maintained to support comfort. Field data monitoring was conducted to develop a calibrated EnergyPlus model to analyze the impact of key design variables on system performance in mixed and cold climate zones (CZs 4–6).

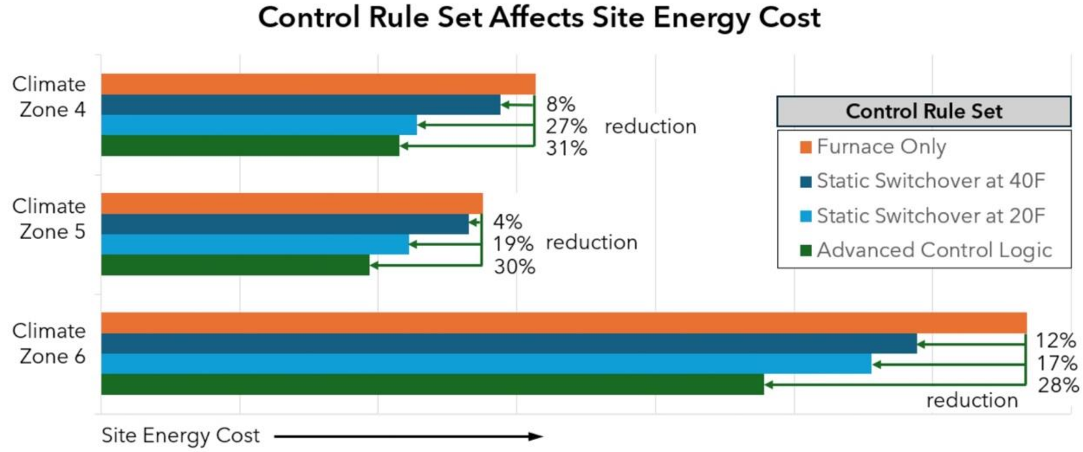


Key Factors Affecting Dual Fuel System Performance

Control Logic	Heat Pump Sizing	Building Tightness	Energy Rate Structure

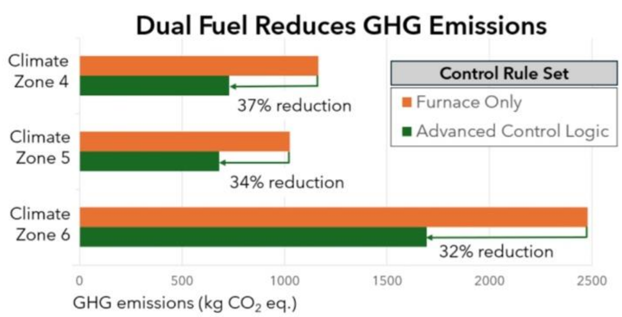
Control Logic: What are the impacts of different control strategies?

3 control strategies for a dual fuel heating system were compared to a furnace-only scenario.
(1) Switchover temperature controls at 40° F (heat pump does not operate below 40° F).
(2) Switchover temperature controls at 20° F (heat pump does not operate below 20° F).
(3) Advanced control logic which selects the heating source (furnace or heat pump) based on the estimated $/Btu of heating, factoring in system efficiency (which depends on outdoor temperature) and energy prices. The logic was specifically developed for this project.

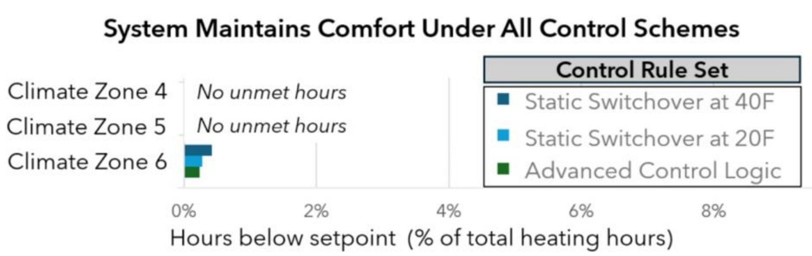


Note: *Site Energy Costs in this fact sheet assume the use of time-of-use electric rates unless noted otherwise. See Key Assumptions section for more information on energy rates.*

The data shows that advanced control logic yields the lowest energy cost in every climate zone, with increased performance gains in the coldest climate zone in the study (CZ 6). Additionally, the use of a 20° F switchover temperature allows more heat pump operation and results in greater cost savings compared to the 40° F switchover temperature. All three dual fuel control scenarios have lower energy costs compared to the furnace-only heating system scenario.



Further, a dual fuel system with advanced control logic has the potential to significantly reduce GHG emissions compared to furnace-only systems. This data incorporates national average emissions rates for electricity from EPA's E-Grid data set.



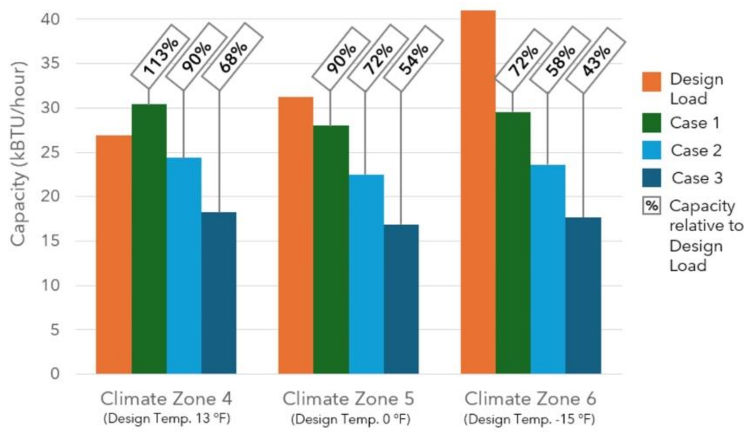
The dual fuel system is very effective at maintaining comfortable indoor conditions near the set point temperature under all three control strategies.

Dual fuel programs can implement lower switchover temperatures or advanced control logic (as available) to reduce operating costs and emissions, while maintaining comfort.

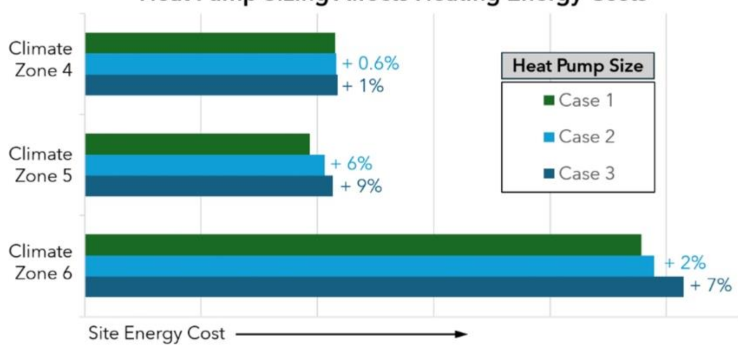
Heat Pump Sizing: What are the impacts of heat pump sizing?

This analysis examined the impact of using a heat pump with varying levels of heating capacity at design conditions relative to the home's design heating load. Case 1 (green) assumed the greatest amount of heating capacity (close to 100% in CZs 4 and 5), Case 2 (light blue) assumed a lower capacity, and Case 3 (dark blue) assumed the lowest capacity.

Heat Pump Capacities Used in Analysis



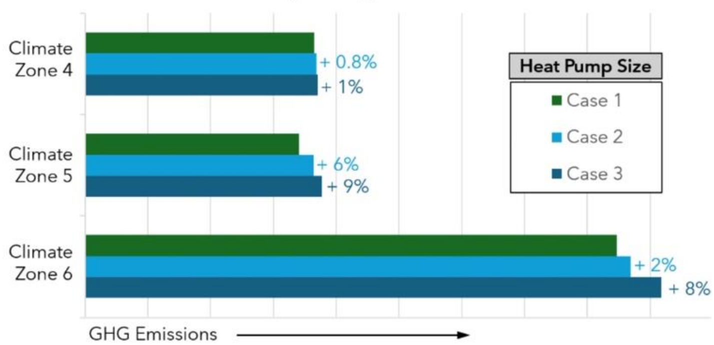
Heat Pump Sizing Affects Heating Energy Costs



Heating energy costs change very little in CZ 4 as heat pump capacity is reduced.

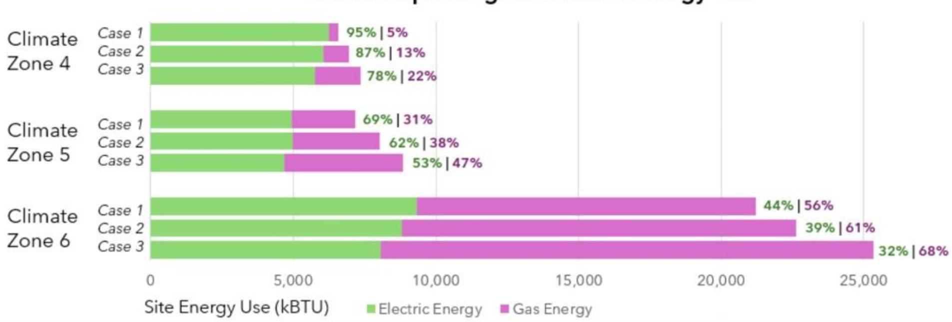
In colder zones, reduced heat pump capacity results in more significant heating energy cost increases. Case 3 is 9% higher than Case 1 in CZ 5, and 7% higher in CZ 6.

Heat Pump Sizing Affects GHG Emissions



Heat pump emissions increase with decreasing heat pump capacity, more significantly in the colder climate zones.

Heat Pump Sizing Affects Site Energy Use

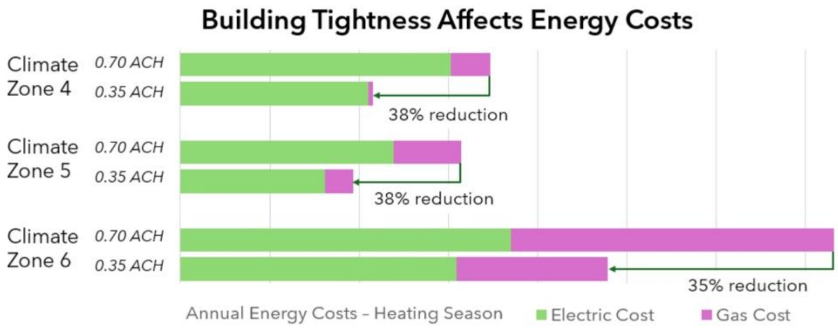


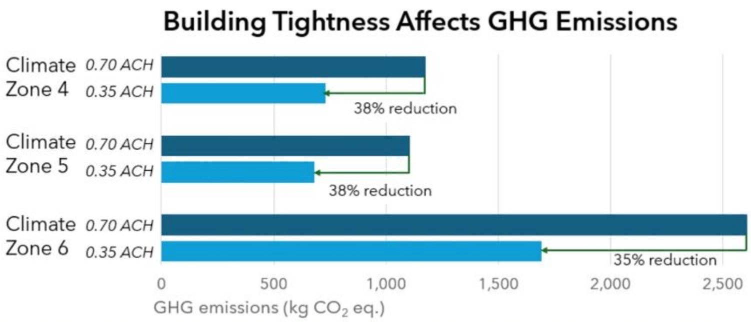
As heat pump capacity is reduced, there is less electricity use and greater gas energy consumption. Total site energy use increases.

Dual fuel incentive programs should encourage variable capacity heat pumps sized to meet most of the home's heating load at design conditions, to the extent possible. System capacity relative to the home's *cooling* load should also be within the heat pump's operation range.

Envelope Tightness: What are the impacts of a leaky building shell?

This analysis examined the impact of a leakier building envelope on the dual fuel heating system performance. The baseline infiltration rate used in this study was 0.35 air changes per hour (ACH), and was compared against a leakier envelope with a leakage rate of 0.70 ACH.





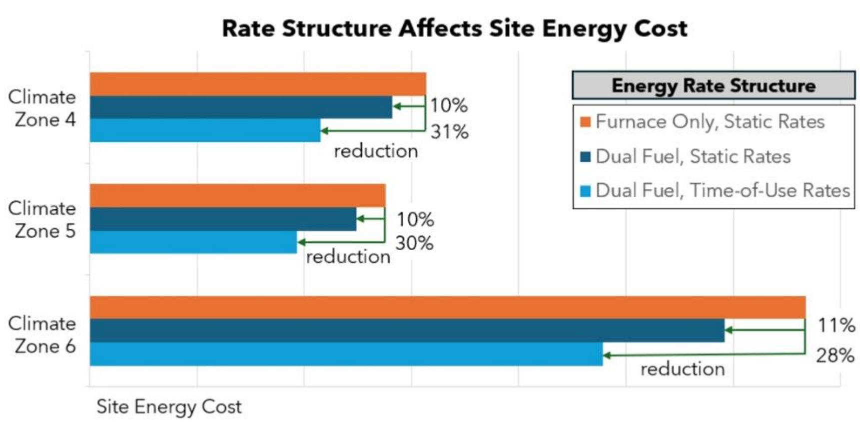
The data shows that a leakier envelope will increase electric costs, gas costs and GHG emissions.

Additionally, the study concluded that hours where the indoor temperature drops below the setpoint increased significantly in the leakier home scenario. This effect was most significant in CZ 6. The leakier home scenario could result in comfort issues.

Dual fuel incentive programs can combine air sealing measures with add-on heat pump implementation to maximize the heat pump's effectiveness and improve comfort.

Energy Rates: How does the rate structure affect site energy cost?

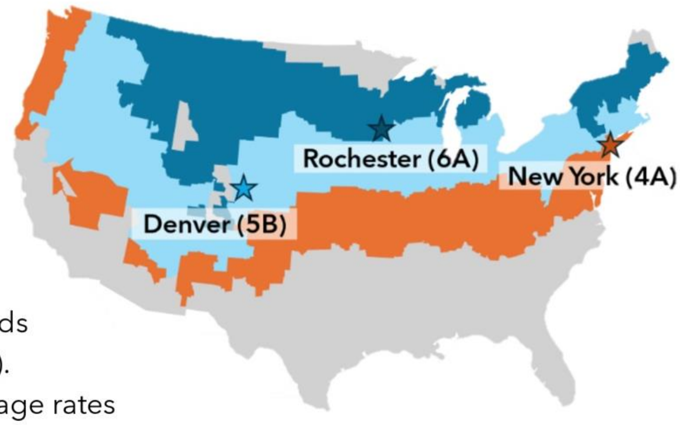
This analysis examined the impact of time-of-use (TOU) electric rates as compared to static gas ($1.42/therm) and electric rates (15.12 cents/kWh) based on national average residential rates. The TOU rates are a 3-tier structure based on rate structures offered by some utilities in mixed/cold climates.



TOU electric rates combined with the control logic that selects the lower $/BTU heating source provides significant cost savings over a dual fuel system operating under static energy rates. A dual fuel system with static gas and electric rates delivers cost savings over furnace-only operation with the same gas rate.

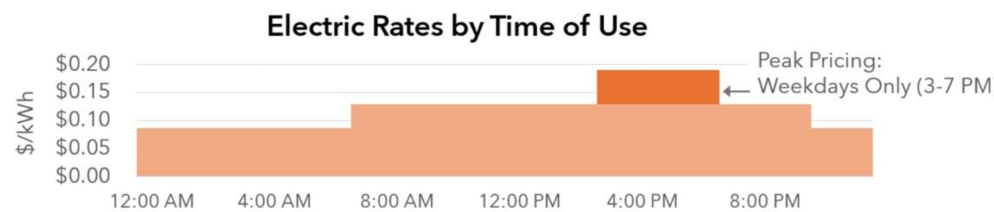
Dual fuel systems with advanced controls can increase cost savings for consumers by taking advantage of electric time-of-use rates, where available.

Key Assumptions



Conducting this analysis required numerous inputs and assumptions, several of which are highlighted below. Stakeholders should review these assumptions relative to their specific circumstances when applying the study findings and conduct additional analysis as necessary.

1. Each ***climate zone*** discussed above corresponds to data from representative cities (see map, right).
2. ***Emissions rates*** for electricity are national average rates sourced from EPA's E-Grid database.
3. ***Gas prices*** in the analysis are based on the 2022 national average residential price, $1.42/therm, sourced from the U.S. Energy Information Administration (EIA).
4. ***Electric rates*** are based on a time-of-use (TOU) schedule to demonstrate the ability of the dual fuel system and its innovative control system used in this study to select the heating source based on varying energy costs. The TOU schedule is based on a composite of 3-tier utility rates in several mixed/cold climate markets, the magnitude of differences between these tiers, and the 2022 national average electric price (15.12 ¢/kWh) from the EIA.



5. All findings are based on ***EnergyPlus modeling***, using a model calibrated by field site monitoring data. Heat pump performance within the model is based on a cold climate heat pump performance curve. The gas furnace in the model has an efficiency of 80 AFUE.

Market Integration

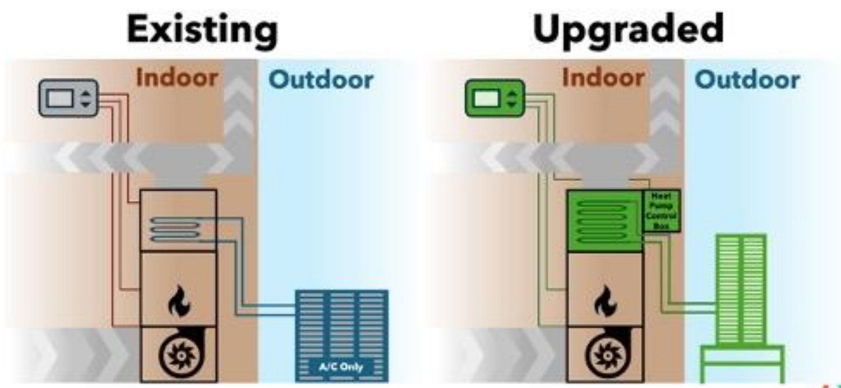
There are currently "add-on" heat pumps which are variable capacity and can integrate with existing furnaces and blowers to create dual fuel heating systems. Controls which allow dual fuel systems to select the heating source based on estimated costs are in development with manufacturers and expected within a few years, while controls offering the ability to set different switchover temperatures are currently available. Based on this research, dual fuel heating systems (especially those offering advanced controls) can offer a retrofit opportunity for gas-heated homes to deliver significant energy, cost, and emissions benefits while maintaining comfort.

Material produced for the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, by Newport Partners, L.L.C., August 2024.

Appendix E: Presentation at AESP Summer Con

A Dual Fuel Heating System Retrofit using Advanced Controls

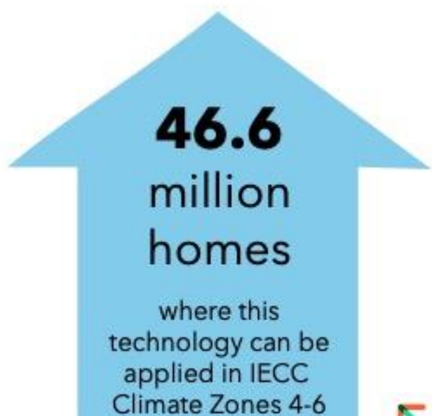
- **Dual Fuel Heating**
- **Retrofit**
- **Control-Optimized**



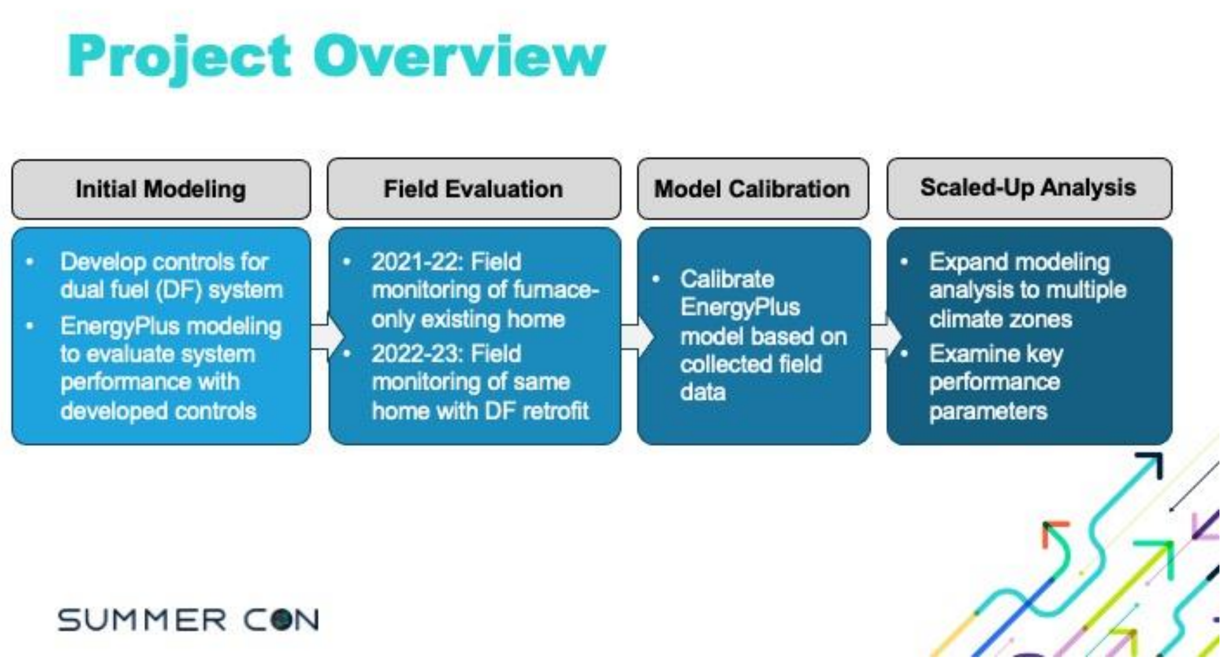
SUMMER CON

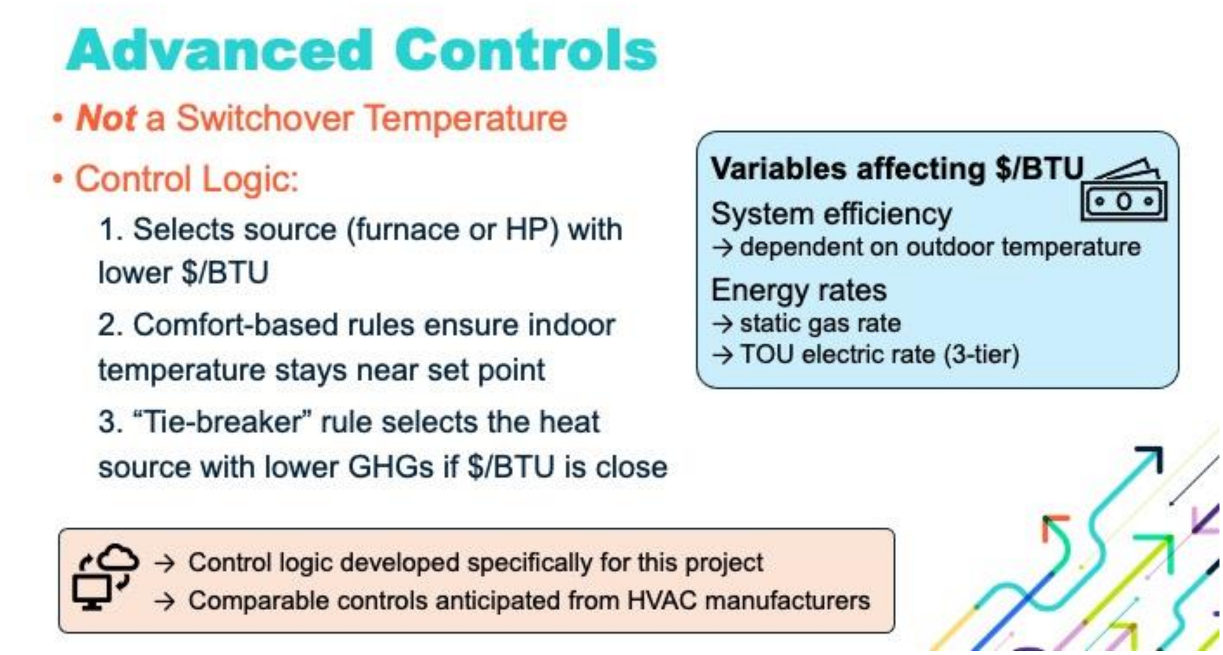
Market Opportunity

- 46.6 million existing homes in U.S. IECC climate zones 4-6 use fossil-based forced-air heating systems
- This retrofit opportunity offers potential benefits related to:
  - Energy savings
  - Energy costs
  - GHG emissions
  - Demand flexibility

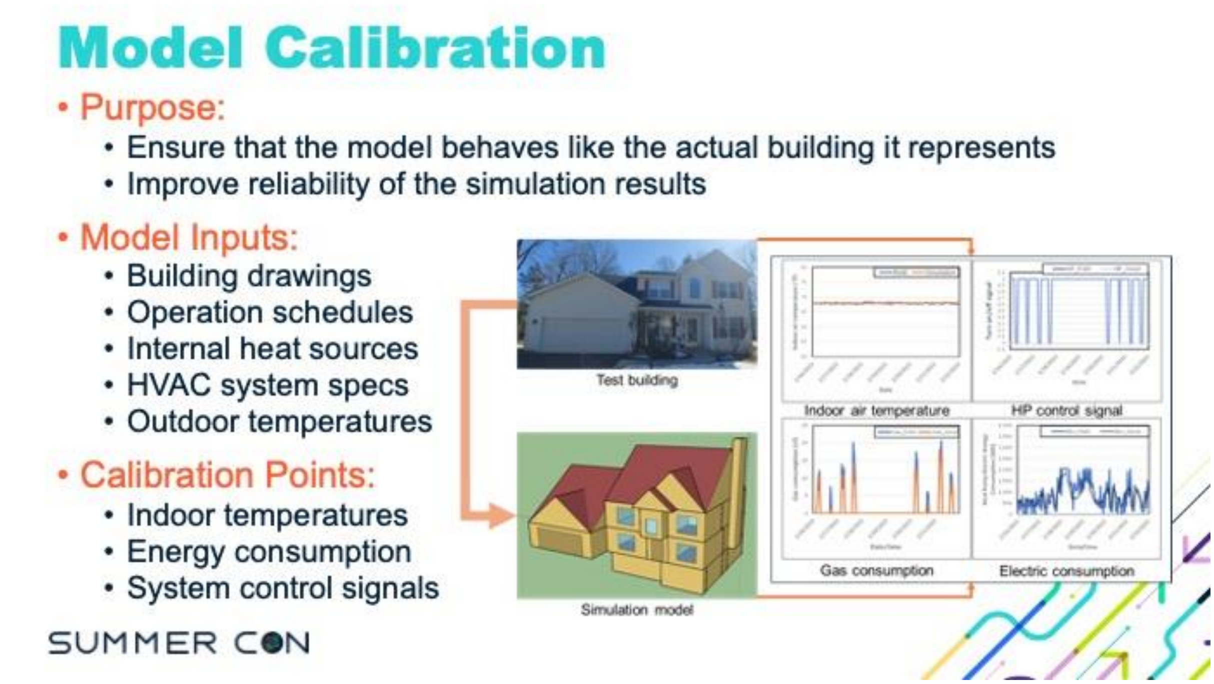


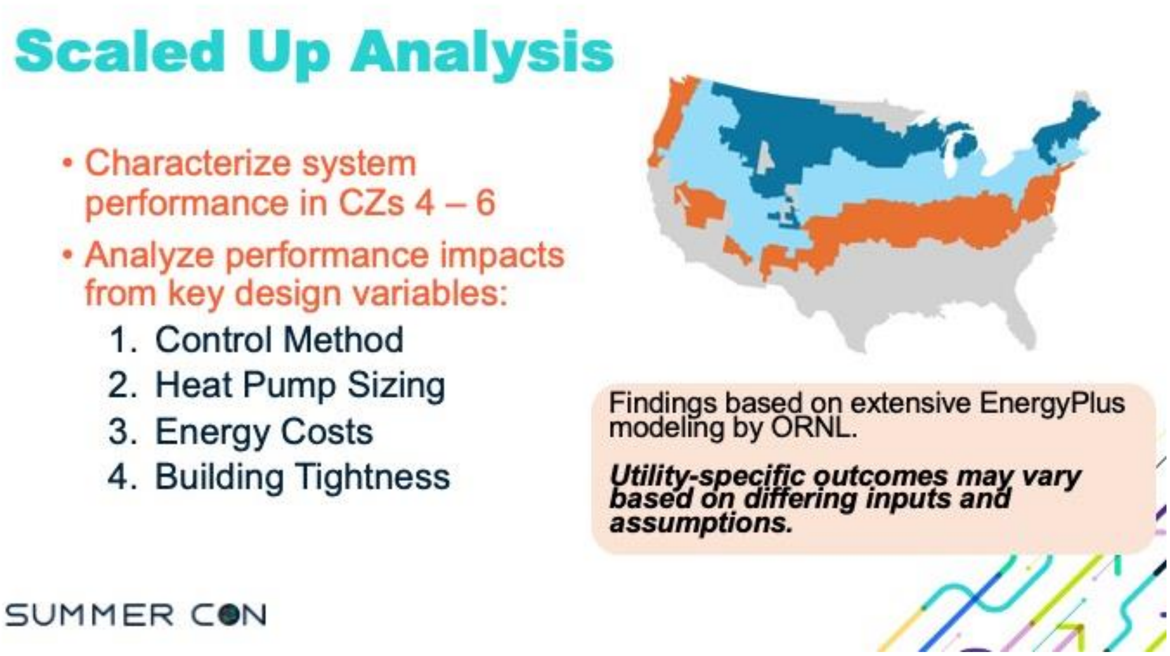
SUMMER CON

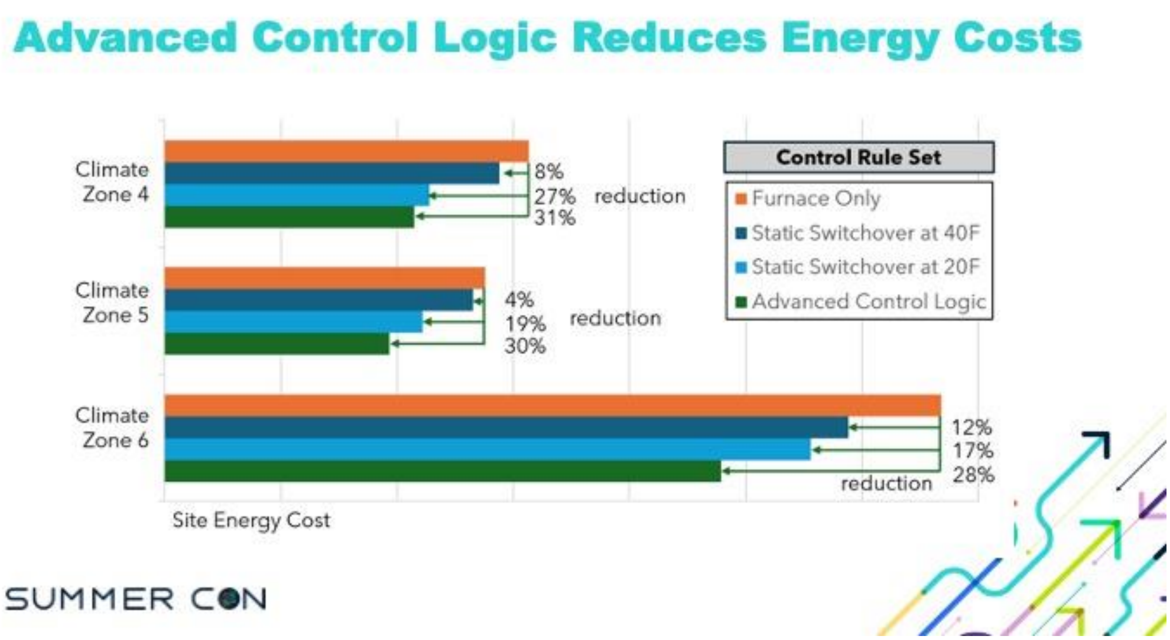

Project Overview
Initial Modeling
Field Evaluation
Model Calibration
Scaled-Up Analysis
• Develop controls for dual fuel (DF) system
• EnergyPlus modeling to evaluate system performance with developed controls
• 2021-22: Field monitoring of furnace-only existing home
• 2022-23: Field monitoring of same home with DF retrofit
• Calibrate EnergyPlus model based on collected field data
• Expand modeling analysis to multiple climate zones
• Examine key performance parameters
SUMMER CON

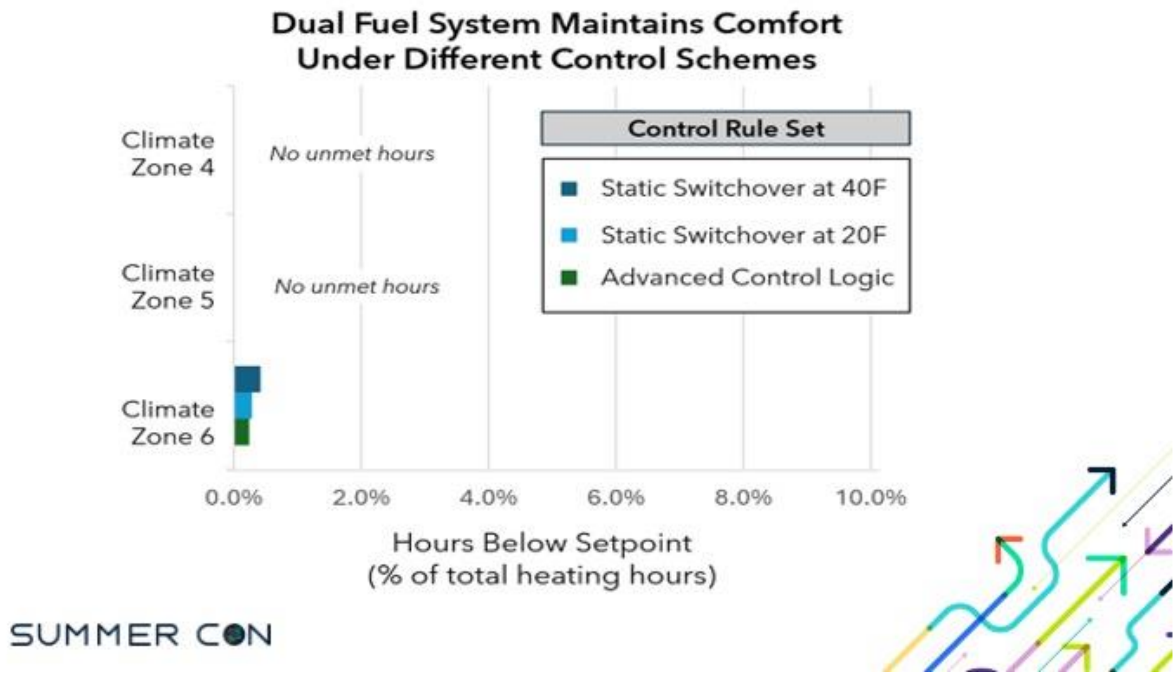

Advanced Controls
• Not a Switchover Temperature
• Control Logic:
1. Selects source (furnace or HP) with lower $/BTU
2. Comfort-based rules ensure indoor temperature stays near set point
3. "Tie-breaker" rule selects the heat source with lower GHGs if $/BTU is close
Variables affecting $/BTU
System efficiency
→ dependent on outdoor temperature
Energy rates
→ static gas rate
→ TOU electric rate (3-tier)
→ Control logic developed specifically for this project
→ Comparable controls anticipated from HVAC manufacturers

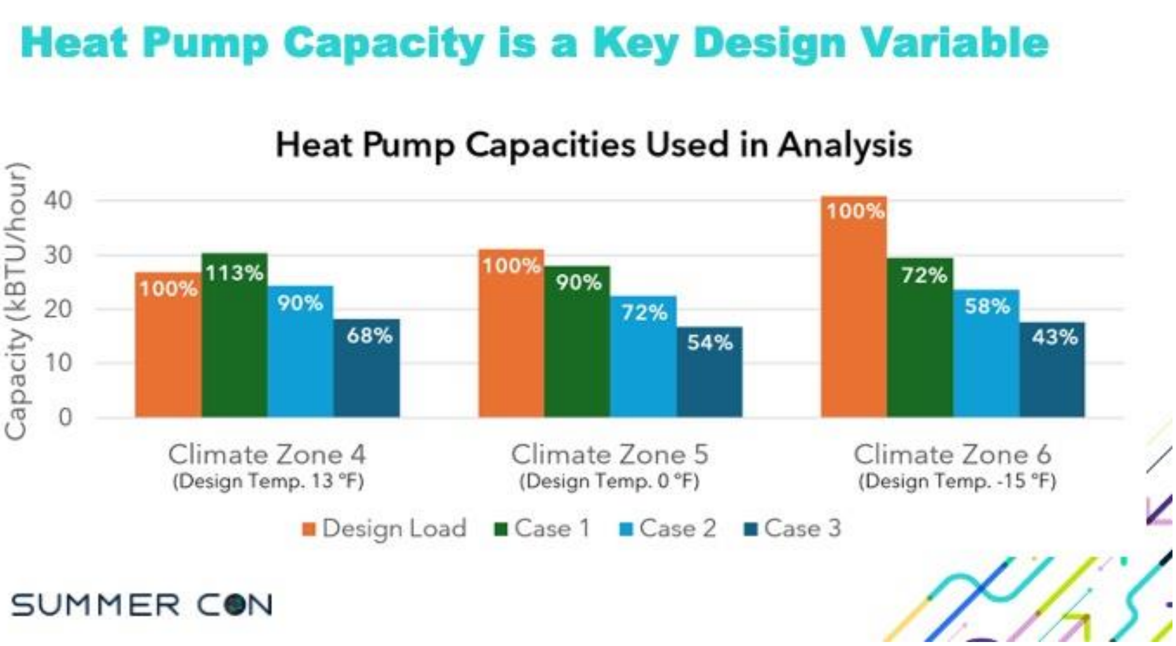

Field Evaluation
Existing home
• Upstate NY
Detailed data monitoring
• Environmental conditions
• HVAC operations
• Energy use
System: Winter 1
• 3-year-old 96 AFUE furnace
• 22- year-old A/C
System: Winter 2
• Existing furnace + Mitsubishi IntelliHeat HP
• Control logic implemented via datalogger
SUMMER CON

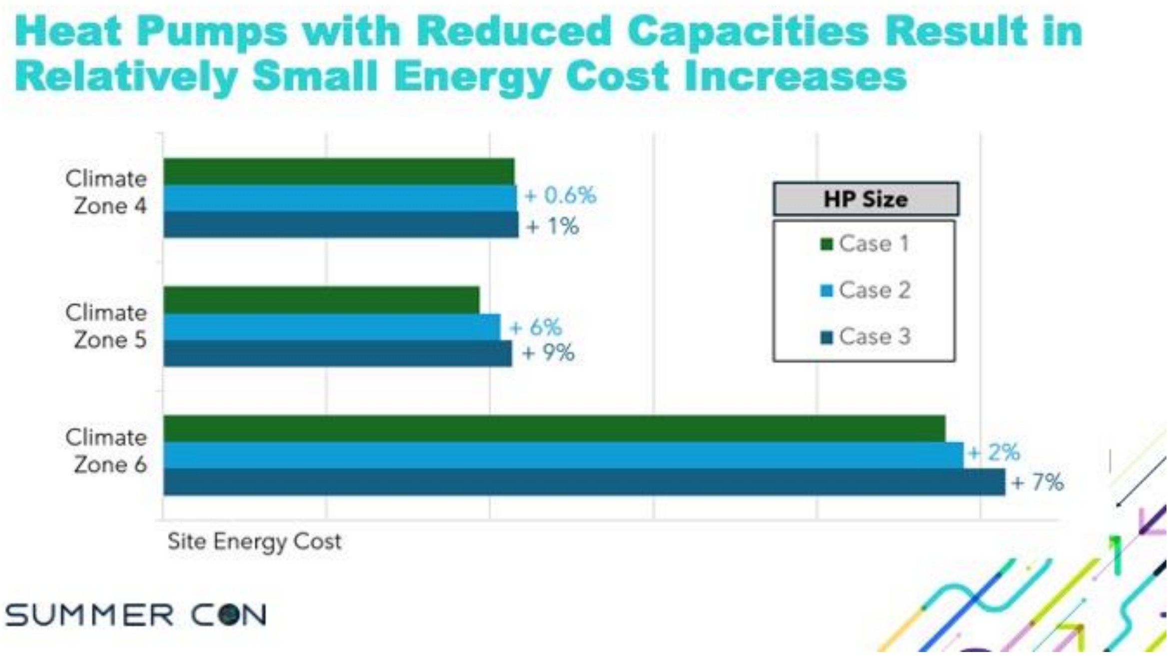

Model Calibration
• Purpose:
• Ensure that the model behaves like the actual building it represents
• Improve reliability of the simulation results
• Model Inputs:
• Building drawings
• Operation schedules
• Internal heat sources
• HVAC system specs
• Outdoor temperatures
• Calibration Points:
• Indoor temperatures
• Energy consumption
• System control signals
Test building
Simulation model
Indoor air temperature
HP control signal
Gas consumption
Electric consumption
SUMMER CON

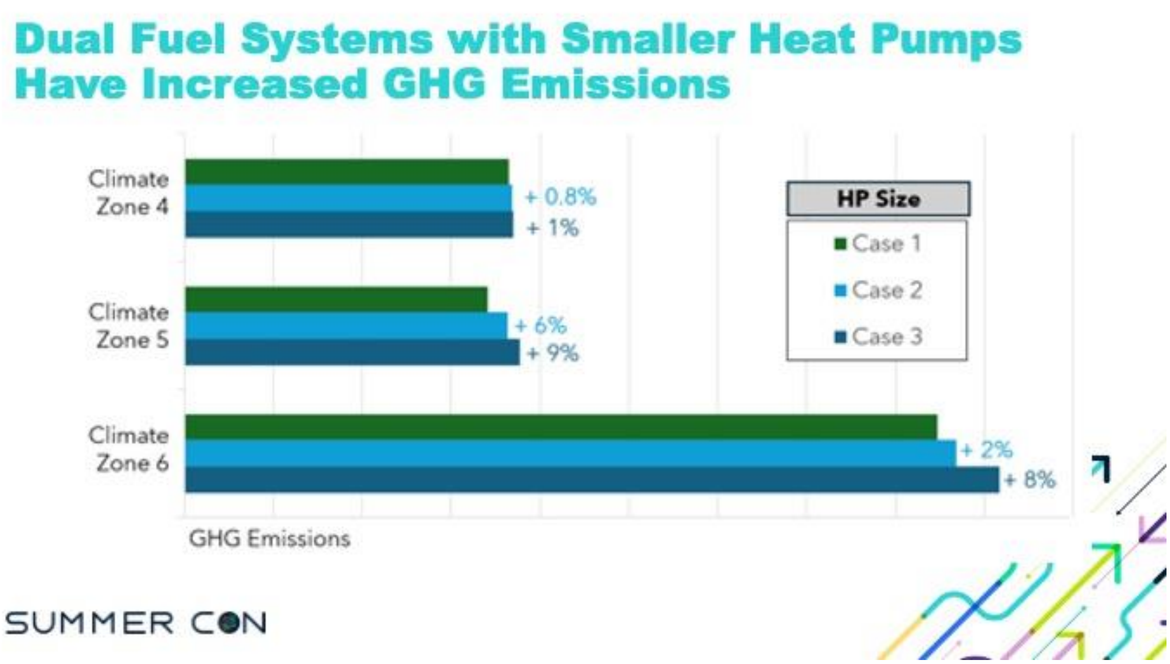

Scaled Up Analysis
• Characterize system performance in CZs 4 – 6
• Analyze performance impacts from key design variables:
1. Control Method
2. Heat Pump Sizing
3. Energy Costs
4. Building Tightness
Findings based on extensive EnergyPlus modeling by ORNL.
Utility-specific outcomes may vary based on differing inputs and assumptions.
SUMMER CON


Advanced Control Logic Reduces Energy Costs
Climate Zone 4
8%
27% reduction
31%
Climate Zone 5
4%
19% reduction
30%
Climate Zone 6
12%
17%
28%
reduction
Site Energy Cost
Control Rule Set
Furnace Only
Static Switchover at 40F
Static Switchover at 20F
Advanced Control Logic
SUMMER CON

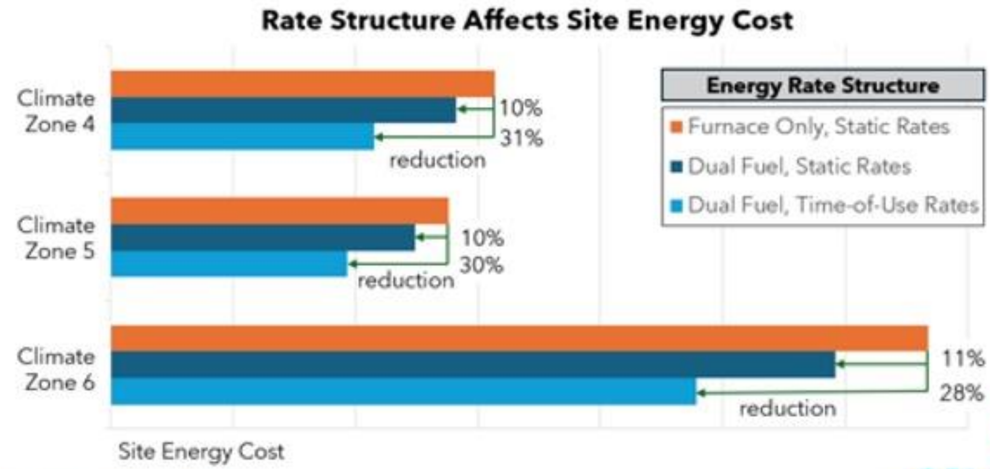

Dual Fuel System Maintains Comfort
Under Different Control Schemes
Control Rule Set
Static Switchover at 40F
Static Switchover at 20F
Advanced Control Logic
Climate Zone 4
No unmet hours
Climate Zone 5
No unmet hours
Climate Zone 6
0.0%
2.0%
4.0%
6.0%
8.0%
10.0%
Hours Below Setpoint
(% of total heating hours)
SUMMER CON


Heat Pump Capacity is a Key Design Variable
Heat Pump Capacities Used in Analysis
Capacity (kBTU/hour)
0
10
20
30
40
100%
113%
90%
68%
100%
90%
72%
54%
100%
72%
58%
43%
Climate Zone 4
(Design Temp. 13 °F)
Climate Zone 5
(Design Temp. 0 °F)
Climate Zone 6
(Design Temp. -15 °F)
Design Load
Case 1
Case 2
Case 3
SUMMER CON


Heat Pumps with Reduced Capacities Result in Relatively Small Energy Cost Increases
Climate Zone 4
+ 0.6%
+ 1%
Climate Zone 5
+ 6%
+ 9%
Climate Zone 6
+ 2%
+ 7%
HP Size
Case 1
Case 2
Case 3
Site Energy Cost
SUMMER CON

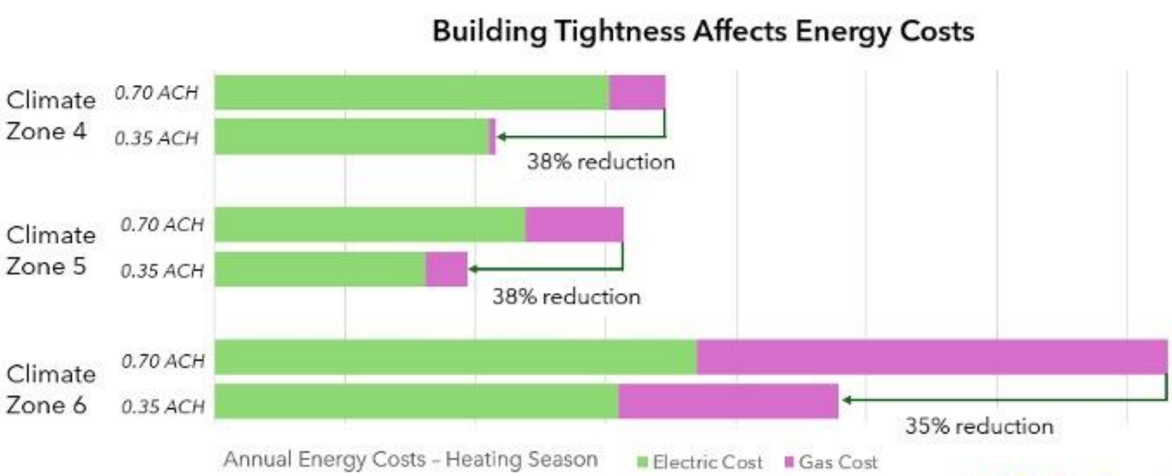

Dual Fuel Systems with Smaller Heat Pumps Have Increased GHG Emissions
Climate Zone 4
+ 0.8%
+ 1%
Climate Zone 5
+ 6%
+ 9%
Climate Zone 6
+ 2%
+ 8%
HP Size
Case 1
Case 2
Case 3
GHG Emissions
SUMMER CON

Dual Fuel Systems w/ Advanced Controls + TOU Rates = Cost Savings



SUMMER CON

Leakier Homes Have Higher Energy Costs and Reduced Comfort



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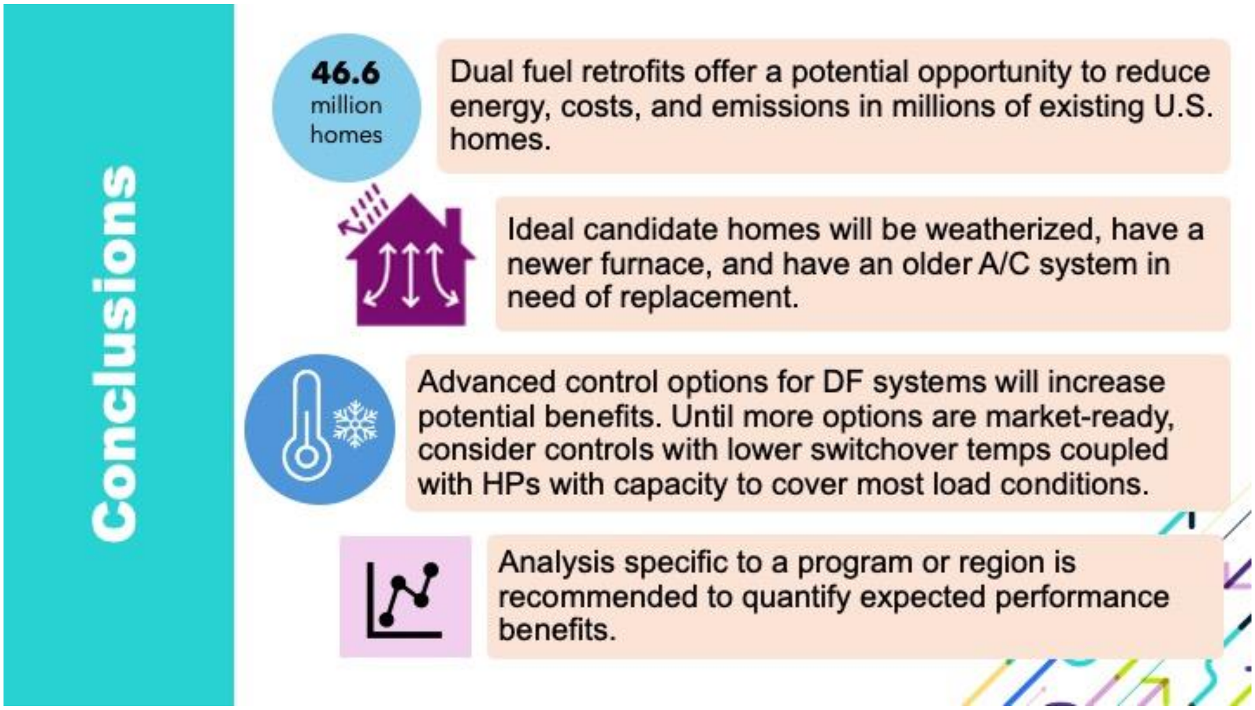
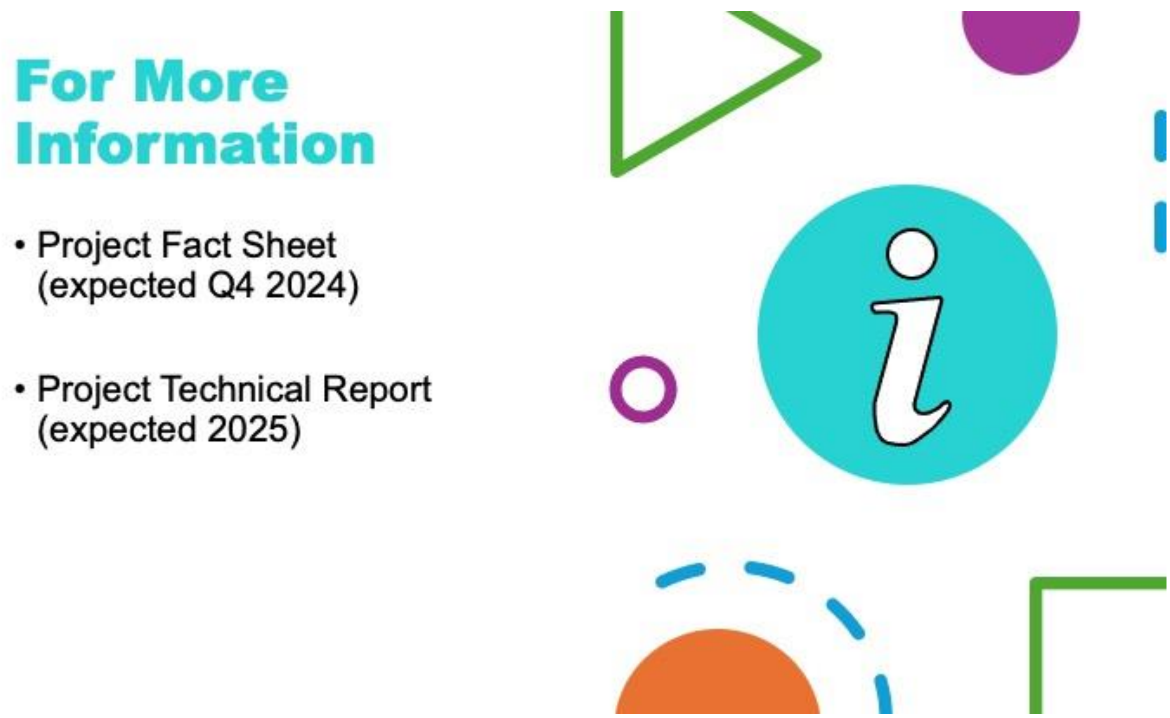
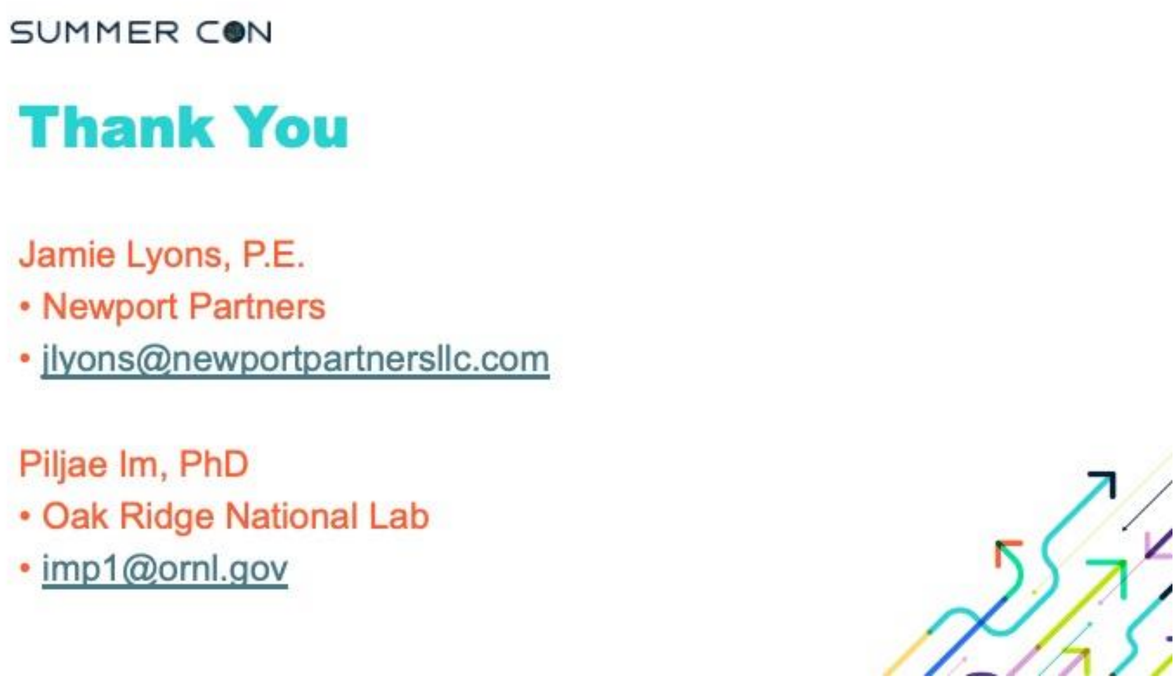

Conclusions
46.6 million homes
Dual fuel retrofits offer a potential opportunity to reduce energy, costs, and emissions in millions of existing U.S. homes.
Ideal candidate homes will be weatherized, have a newer furnace, and have an older A/C system in need of replacement.
Advanced control options for DF systems will increase potential benefits. Until more options are market-ready, consider controls with lower switchover temps coupled with HPs with capacity to cover most load conditions.
Analysis specific to a program or region is recommended to quantify expected performance benefits.


For More Information
• Project Fact Sheet (expected Q4 2024)
• Project Technical Report (expected 2025)


SUMMER CON
Thank You
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