An Affordable, Minimum-carbon Hybrid Heat Pump with a Grid-Responsive Retrofittable Controller

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ABSTRACT

This research demonstrates the efficacy of a dual fuel heat pump controller that can accelerate the transition from fossil fuel-based heating to electrified space heating, driving both affordability and widespread adoption, ultimately contributing to the broader objective of decarbonization. The grid-responsive controller allows a low-cost universal retrofit to enable partial electrification from existing furnaces to dual fuel heat pumps. This provides an affordable path towards electrification for older and high load homes that would otherwise require an expensive upgrade of electrical service to accommodate electric resistance backup heat. Furthermore, the research identifies opportunities where smart controls, responsive to marginal grid emission signals, can have lower total CO_2 emissions than conventional electric heat pumps.

Many dual fuel, or “hybrid,” heat pumps lack intelligent control mechanisms to efficiently manage the switch between heat pump and furnace, leading to overreliance on fossil fuels, sub-optimal carbon emissions, and, in some cases, increased operating costs. To address this, the study developed dual fuel heat pump controls optimized to minimize utility costs and GHG emissions for multiple climate zones, utility tariffs, and marginal grid emission scenarios.

To analyze the national impact of the controller, a co-simulation framework based on EnergyPlus and DOE/ORNL Heat Pump Design Model is used to compare the performance of conventional heat pumps, conventional furnaces, dual fuel heat pumps with conventional controls that use furnaces as supplemental heating devices, and dual fuel heat pumps with grid-responsive controls. Case studies demonstrate the dual fuel heat pump can deliver significant reductions in peak demand, utility cost, and CO_2 emission.

Introduction

In response to anthropogenic climate change, the United States has enacted strategies encompassing renewable energy utilization and energy efficiency enhancement to curtail energy demand and greenhouse gas (GHG) emissions. The Biden administration's inaugural executive directive in 2021 delineated a framework to halve the carbon footprint of the U.S. building inventory by 2035, with a broader ambition to facilitate a clean energy transition and achieve net-zero emissions by 2050. Despite the primary objective of phasing out fossil fuels, there's a recognized necessity to augment the efficiency of current fossil fuel-dependent building systems during the interim towards a zero-emission future. Enhancing the operational efficiency of these systems is pivotal for substantial GHG emission and energy consumption reductions.

Heat pumps are recognized as an energy-efficient and environmentally friendly heating solution compared to traditional fossil fuel-based appliances. However, the barriers to widespread adoption have been numerous: high initial investment costs, the high cost to ratepayers of electricity relative to other heating fuels in some regions, concerns over the effectiveness in colder climates, and the inertia of homeowners and businesses already invested in existing heating infrastructures. The dual fuel heat pump provides desirable solutions to these concerns. These systems are designed to allow the heat pump to provide heat to the home during most of the year and only operate the gas furnace for the very coldest ambient conditions, thus allowing almost complete decarbonization of the home's heating system. By allowing systems to switch between the heat pump and a fossil fuel furnace, it ensures optimal heating performance even in extreme temperatures. Using the existing furnace will reduce the cost of installation, especially in retrofits, which could require an upgrade to their electrical service to allow the use of electric resistance heating elements for supplementary heat. For typical dual fuel heat pump controls, furnace heating is triggered during severe cold spells where heat pump efficiency and capacity diminish. This auxiliary heating engagement occurs at a defined balance point, where economic considerations favor furnace activation over heat pump operation due to diminished heat pump efficiency and capacity. This balance or transition threshold can be programmed within the thermostat or the heat pump's controller.

Meanwhile, the electricity sector has seen a shift from traditional isolated systems to smart grid devices (Alibabaei et al. 2017). This phenomenon has been ushered in by the increased integration of renewable energies. The rapid proliferation of the 'Internet of Things' (IoT) (Siano 2014) allow major loads, such as heat pumps, to be controlled with the goal of reducing peak power consumption on the electrical grid. In a smart grid, heat pumps can be considered part of the demand side that can be actively managed to stabilize voltage fluctuations caused by high demand or high penetration of renewable energy (Fischer and Madani 2017). With smart control of DFHP, the system can switch between furnace and heat pump mode depending on the outdoor temperature, gas and electricity prices, desired indoor temperature, renewable energy generation, and heat pump's COP (Siano 2014).

It is important to describe how to incorporate a grid's greenhouse gas (GHG) condition into a site-specific model predictive control (MPC). The grid system-wide emission rate in a specific grid region depends on the total power production rate from grid power generators, and other factors that affect system operating conditions, such as weather. The marginal operating emissions rate (MOER) is the partial derivative of the systemwide emission rate with respect to the total production rate (Callaway, Fowlie, and McCormick 2018). It means the change of the emission rate in the grid region with respect to the last megawatt produced by dispatchable generators having the unit of metric Ton CO2-equivalent per MWh [mTonCO2e/MWh]. Intuitively, this indicates how much carbon emission rate increases/decreases in a grid region when one consumes one megawatt more/less. Therefore, MOER allows for associating the power usage at a specific site with the carbon emission rate in the grid region by simply multiplying the on-site power consumption with the MOER signal.

In this paper, we used the MOER signal calculated by WattTime, based on a proprietary model that extends the basic methodology used by Siler-Evans et al (Siler-Evans et al. 2013) and Callaway et al (Callaway, Fowlie, and McCormick 2018), but adapted for real-time use. WattTime calculates these marginal operating emission rates in real-time, every 5 min using a combination of grid data from the respective ISO and 5 years of historical Continuous Emissions Monitoring System data (Agency 2018). Figure 1 shows a demonstration of WattTime data on April 7th, 2023 for four major US grid balancing areas, i.e., California Independent System Operator (CAISO), The New York Independent System Operator (NYISO), Western Interconnection Balancing Authorities (WACM) and Southwest Power Pool (SPP).

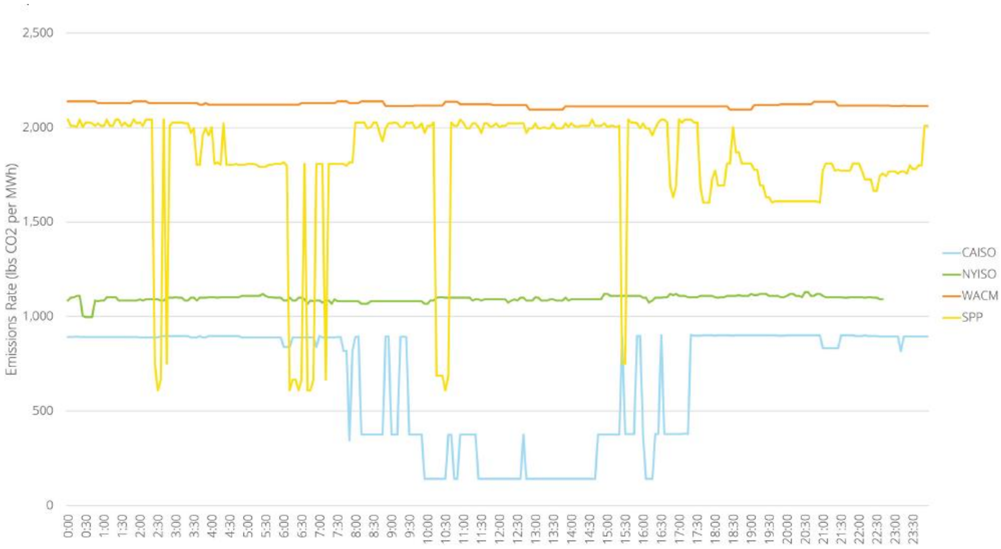

Figure 1: Marginal Operating Emissions Rates for Four Representative US Grid Balancing Areas, April 7, 2023

Whereas the utility peak in a time-of-use utility scheme is not necessarily consistent with the peak of MOER. Figure 2 shows the TOU structure of Chicago's ComEd utility company and the MOER in Chicago for the same day.

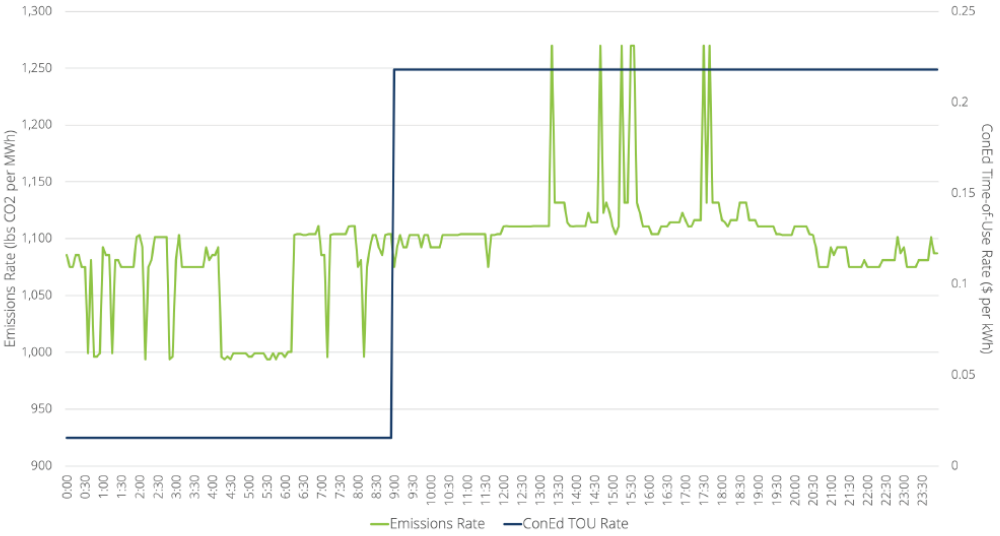

Figure 2: NYISO Emissions vs ComEd Time-of-Use Rate, August 25, 2022

As a summary, the existing dual-fuel heat pumps (DFHPs) lack the intelligent control mechanisms to efficiently manage the switch between heat pump and furnace, leading to sub-optimal energy usage and, in some cases, increased operating costs. Therefore, a notable interim solution presenting a balance between economic viability and environmental sustainability is the DFHP, which integrates an electric heat pump with a natural gas furnace, demonstrating a strategic compromise during the transition phase (Yu et al. 2019). To overcome these challenges, we aim at developing a retrofittable dual fuel heat pump controller with a smart control algorithm that can accelerate the transition from fossil fuel-based heating solutions to full electrification of space heating technology, driving both affordability and widespread adoption, ultimately contributing to the broader objective of decarbonization. This paper demonstrates the efficacy of an advanced DFHP control algorithm aimed at optimizing energy consumption and minimizing CO_2 emissions, addressing the operational challenges.

The Methodology section of the paper is organized as follows: sub-section 2 describes the retrofittable controller. sub-section details the co-simulation framework for conducting modeling. sub-section and sub-section describe the control algorithms for different heating devices. Sub-section 6 demonstrates the efficacy of DFHP with smart controller using two case studies in Los Angeles and Chicago. The Conclusion section summarizes the findings.

Methodology

A Retrofittable controller for DFHP Heat Pump

A universal replacement DFHP controller is proposed, and it allows a heat pump to be added to a residential heating, ventilation, and air conditioning (HVAC) system currently using a gas furnace. The controller will enable a lower-cost method of changing the heating of a home from being fueled solely by the combustion of fossil fuel to being nearly completely electrified. The controller negates the need for an expensive electrical service upgrade to the home and will be able to use the most common existing thermostat wiring, which can have as few as four conductors. The wiring of the controller is illustrated in Figure 3. These characteristics are important to owners of older homes desiring to decarbonize their heating system.

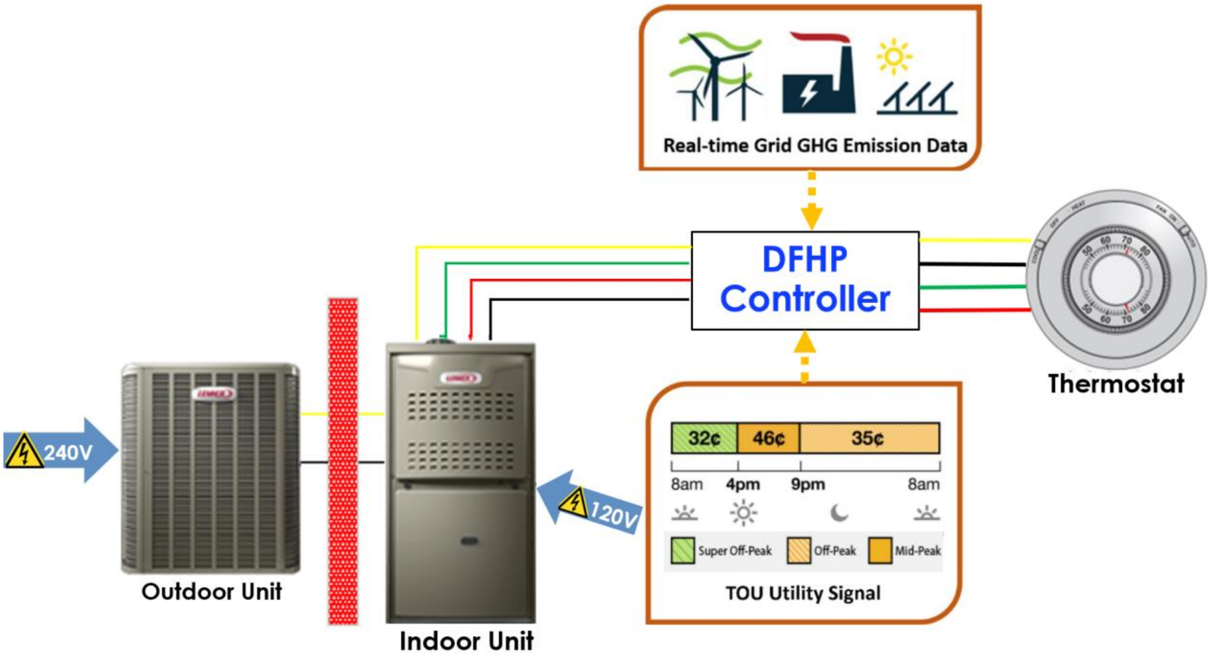

Figure 3: Wiring Schematic of the Retrofittable Controller for Dual Fuel Heat Pump

Starting with an installation of a gas furnace with air conditioning and as few as four conductors in the home's thermostat wiring, a homeowner will be able to have only a new heat pump and this controller added to their system to create a dual fuel heating system that can use either electricity or the fossil fuel as an energy source for heating. For a DFHP heat pump with conventional control strategy, nearly all the heating needs can then be met by the heat pump with the fossil fuel only needed for the coldest days when the heating capacity of the heat pump is not sufficient. For a DFHP heat pump with smart control, the system can receive signals through the grid to change from electric heat pump to fossil combustion heat to relieve pressures on the electric grid that may arise before the electric grid is fully capable of meeting the country's future electrification targets.

EnergyPlus-HPDM Co-simulation Framework

To evaluate the impact of the DFHP system with control algorithms, a co-simulation framework consisting of EnergyPlus and DOE/ORNL Heat Pump Design Model (HPDM) is developed. EnergyPlus provides detailed building envelope simulation modeling and HPDM performs modeling of the DFHP system. The control algorithms are implanted in EnergyPlus Python Plugin as shown in Figure 4. EnergyPlus-Python Plugin serves as a ‘virtual thermostat’ by wiring the virtual equipment (i.e., the DFHP model in HPDM), the virtual building envelope (i.e., the building model in EnergyPlus). Time-of-Use utility scheme and MOER signal is also integrated via EnergyPlus-Python Plugin.

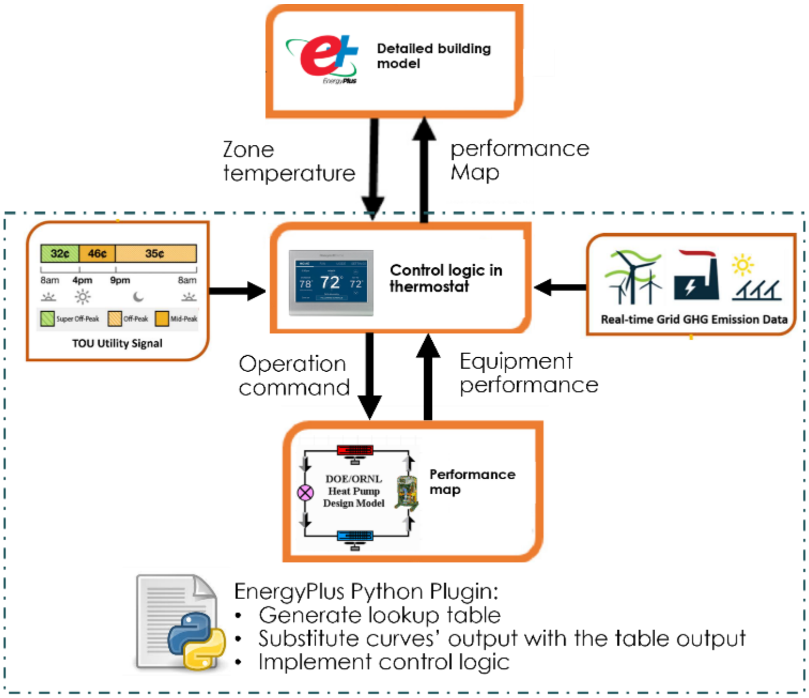

Figure 4: EnergyPlus-HPDM Co-simulation Framework for Dual Fuel Heat Pump

Regarding the building model, a single-family detached house from EnergyPlus prototype building based on the International Energy Conservation Code (IECC) 2015 provided by the Building Energy Codes Program is used for case study. This single-family house has 2,235 ft^2 with the simulation inputs shown as Table 1.

Table 1: EnergyPlus Input Values

Variables		**Input value**
U-value ($W/m^2 \cdot K$) U-value ($W/m^2 \cdot K$)	Exterior wall	0.42
	Roof	0.392
	Window	0.46
Infiltration (ACH)		0.205
People (#)		4
Lighting (W/m^2)		2.1
Electric equipment (W)		124
Heating setpoint (°C)		20 (4 a.m. to 10 p.m.)
Heating setback setpoint (°C)		17.2 (10 p.m. to 4 a.m.)

To model the performance of heat pump and gas furnace, DOE/ORNL Heat Pump Design Model (HPDM) (Shen and Rice 2016) is used. HPDM is a public-domain HVAC equipment and system modeling and design tool which supports a free web interface and a desktop version for public use. In this study, a 3-ton cold climate heat pump is used as the sub-system of SFFHP. The rated heating capacity is 10.55 kW in heating mode and 10.64 kW in cooling mode under AHRI 210/240 test standards (AHRI 2008). Figure 5 shows the performance of the heat pump at different outdoor temperature. This model is validated against experiment data (Munk, Shen, and Gehl 2021). The natural gas furnace is a commercial product with 1200 CFM as maximum air flow rate and 95% as the rated Annual Fuel Utilization Efficiency (AFUE). The natural gas energy density used in the simulation is 10.395 kWh/m^3.

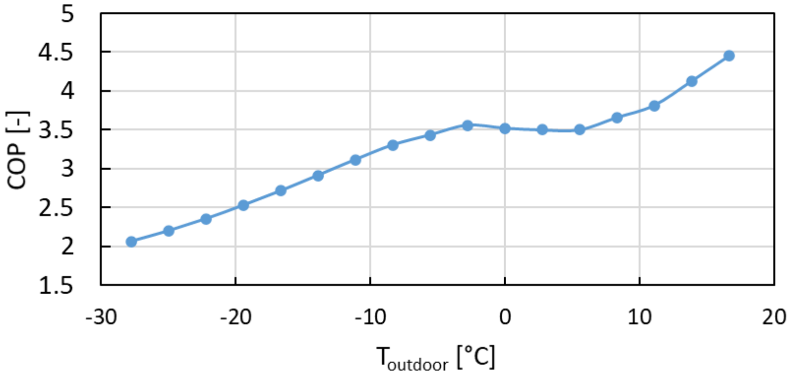

Figure 5: Performance of 3-ton electric heat pump

Control Logic for Baseline Equipment

Natural gas furnace implements a relatively simple control logic than heat pump. The furnace initiates heating when indoor temperatures dip slightly below the thermostat's target, typically by 1-2 degrees Fahrenheit (in the simulation case study presented later, this temperature threshed is set as 1°F), to avoid underheating. Upon activation, the furnace enters a heating cycle, aiming to elevate the ambient temperature to the set level, and maintains operation until the thermostat's vicinity air meets the setpoint, promoting uniform and efficient heating. The cycle concludes with the furnace shutting off as soon as indoor temperatures achieve or marginally exceed the setpoint, a measure to curb energy excess and prevent an overly warm interior. This control strategy as illustrated in Figure 6 (a), centering on maintaining predetermined temperature thresholds, underscores the balance between ensuring occupant comfort and optimizing energy usage.

The control logic for an electric heat pump equipped with electric resistance backup heating is illustrated in Figure 6 (b). This system's operational thresholds, including activation and deactivation temperatures for both the heat pump and its electric resistance backup, depend on the heat pump model, user preferences, and thermostat programming. Generally, the heat pump serves as the primary heating source, optimally functioning in moderate to slightly cold conditions, typically activating above outdoor temperatures such as 35°F. This range is deemed efficient for heat extraction from outdoor air. However, as temperatures dip below the efficiency threshold, heat pump shifts to electric resistance heating. This transition occurs when the heat pump struggles to maintain set indoor temperatures or when its operation becomes energetically unfavorable due to colder external conditions. Electric resistance heating takes over under these circumstances, ensuring continued comfort by compensating for the heat pump's reduced efficiency or inability to achieve the thermostat's setpoint. This backup system deactivates once the indoor temperature meets the desired setpoint or when external temperatures rise sufficiently for the heat pump to reassume its role efficiently.

The control logic of a conventional dual fuel heat pump is similar to an electric heat pump, the difference is mainly the use of a furnace as backup heat instead of electric resistance. Primarily, the electric heat pump operates during milder conditions, efficiently heating by extracting warmth from the outside air, typically activated when indoor temperatures drop below the thermostat's setpoint and outdoor temperatures remain within an approximate range of 35°F to 40°F (1.7°C to 4.4°C). As outdoor temperatures fall below this range, diminishing the heat pump's efficiency, the system switches to the natural gas furnace, leveraging its higher efficiency in colder weather. This transition is guided by a predetermined temperature threshold, although specific transition points may adjust based on system design, user settings, and fluctuating energy costs. The furnace then maintains the heating until indoor temperatures achieve the desired setpoint. Should outdoor temperatures ascend past the threshold where the heat pump's efficiency surpasses that of the furnace, the system reverts to heat pump mode. This control logic illustrated in Figure 6 (c) ensures optimal heating efficiency and comfort, dynamically selecting the most energy efficient.

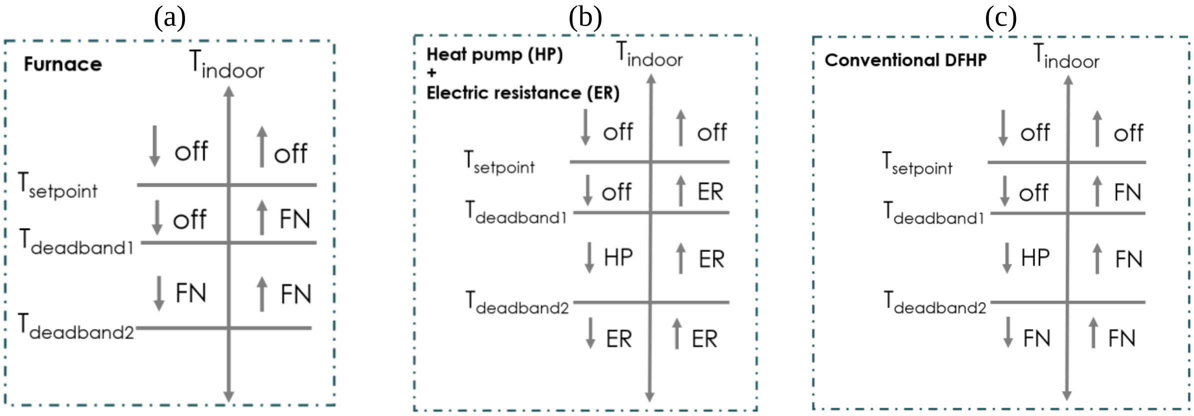

Figure 6: Control logics for baseline heating equipment: (a) furnace; (b) heat pump; (c) dual fuel heat pump with conventional control.

Control Logic for Dual Fuel Heat Pump with Smart Controller

DFHP systems dynamically switches between the heat pump and furnace, considering outdoor temperatures, electricity and gas prices, and the carbon intensity of the electricity supply. This ensures that the DFHP operates in the most cost-effective and environmentally friendly manner possible at any given time. This smart controller also include pre-heating using the heat pump before a cold spell hits or before electricity prices peak, and similarly, switching to the furnace preemptively if high grid emissions are expected. The goal of smart control logic is to achieve a balance between maintaining indoor comfort, minimizing heating costs, and reducing the carbon footprint by selecting the most appropriate heat source in real-time.

At any given time, whether to run heat pump or furnace is decided by comparing the objective functions such as utility cost and CO_2 emission. For instance, at a specific moment, if the user tends to save cost, one of the system yielding less energy cost is activated while the other maintains to be off. By comparing the utility cost and/or the real-time emission, DFHP switches between 2 modes, i.e., HP preferred mode, furnace preferred mode and regular heat pump and furnace's on/off based on sensed indoor temperature as shown in Figure 7 (b).

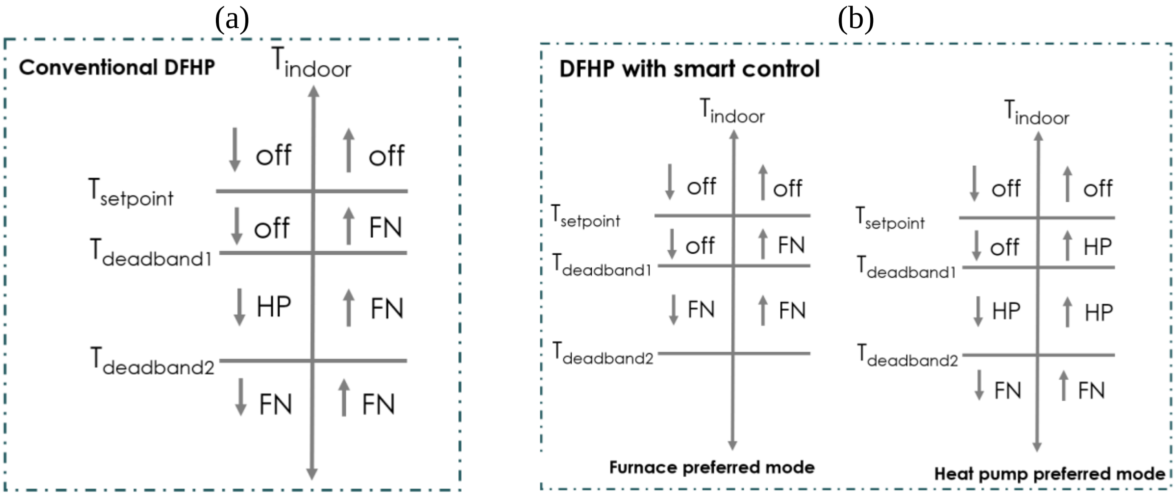

Figure 7: Control logic comparison (a) conventional dual fuel heat pump; (b) smart dual fuel heat pump.

Case Study in Los Angeles and Chicago

The performance of DFHP with conventional control, smart control and the performance of baseline heat pump with electric resistance, baseline furnace are evaluated using Los Angeles and Chicago using the Time-of-Use scheme and MOER signal for entire year 2022, i.e. 8766 hours. Figure 8 shows dry bulb temperature for Los Angeles and Chicago.

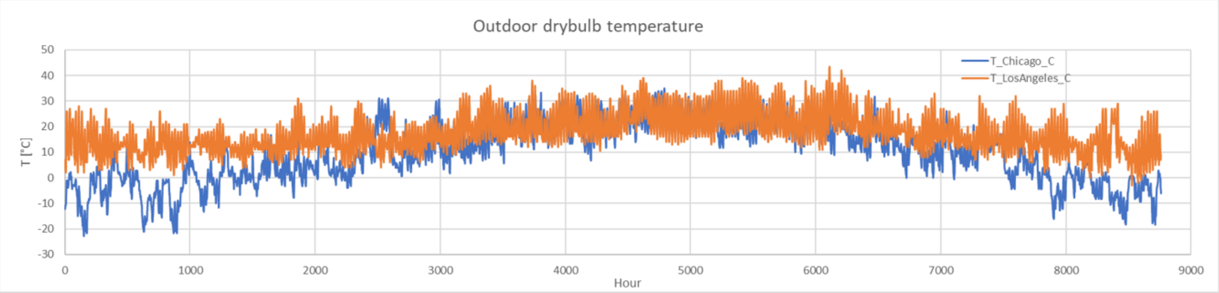

Figure 8: Hourly Dry Bulb Temperature for Los Angeles and Chicago from 1/1/2022 to 12/31/2022

Figure 9 shows the heating demand of the prototype single-family house in Los Angeles and Chicago.

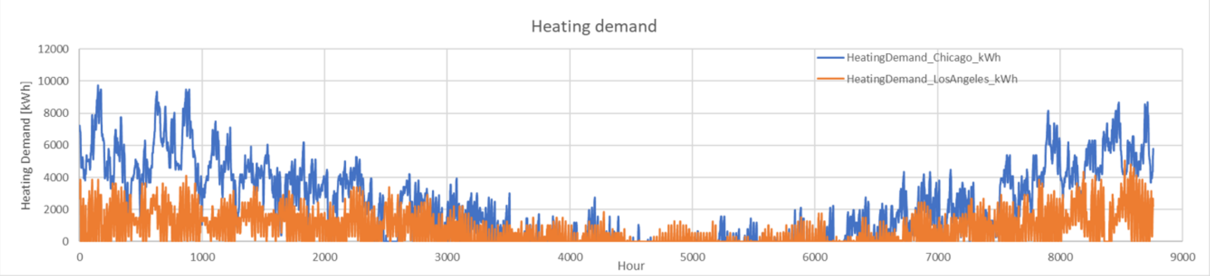

Figure 9: Heating Demand for Los Angeles and Chicago from 1/1/2022 to 12/31/2022

Figure 10 shows the marginal grid emission (MGE) data Los Angeles and Chicago. The grid in Los Angeles has more renewable mix, and thus cleaner. The average MGE is 617 g CO_2/kWh in Los Angeles compared with 856 g CO_2/kWh in Chicago.

For Los Angeles (Figure 11 (a)), the Time-of-Use utility rate is adopted from Southern California Edison (SCE) and the natural gas price is adopted from SoCalGas. The utility company that covers Los Angeles is The Los Angeles Department of Water and Power (LADWP). The study used the TOU rate from Southern California Edison (SCE) because in the next stage of this project, a field test is to be conducted in Riverside, California. Riverside is 60 miles from Los Angeles.

The electricity price ranges from 25 to 44 cents per kWh, while the gas is only 4.27 cents per kWh. For Chicago (Figure 11 (b)), the Time-of-Use utility rate is from ComEd company, and the natural gas price is adopted from Peoples Gas company as indicated. The electricity price in Los Angeles is much more expensive than that in Chicago. And the difference of gas and electricity price is more significant in Los Angeles.

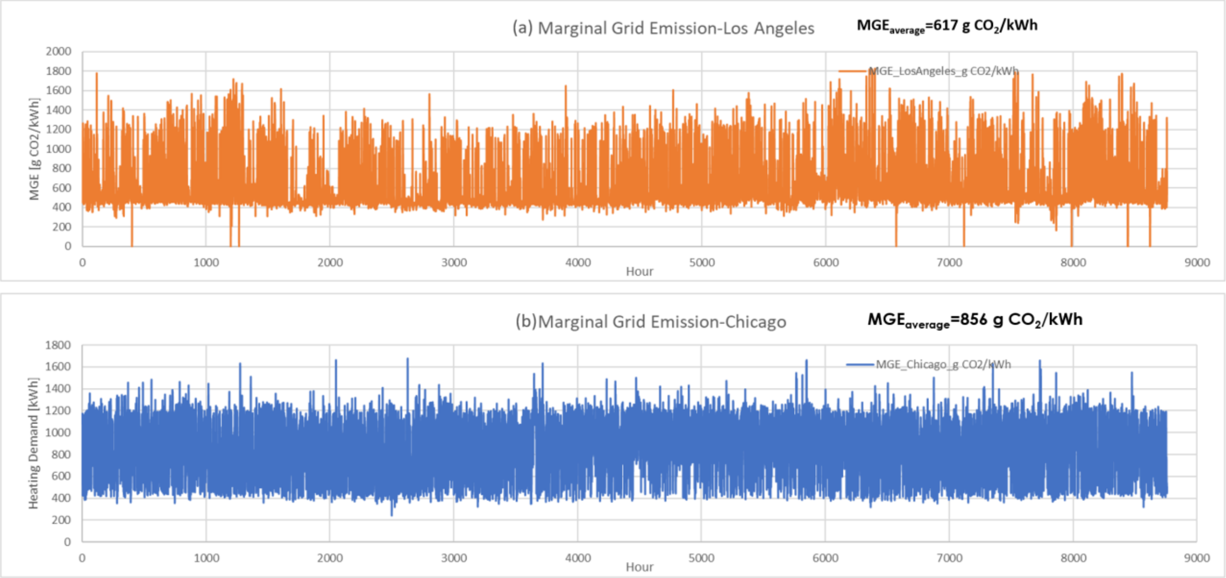

Figure 10: Marginal Grid CO$_2$ Emission for 8766 hours in (a) Los Angeles and (b) Chicago in 2022

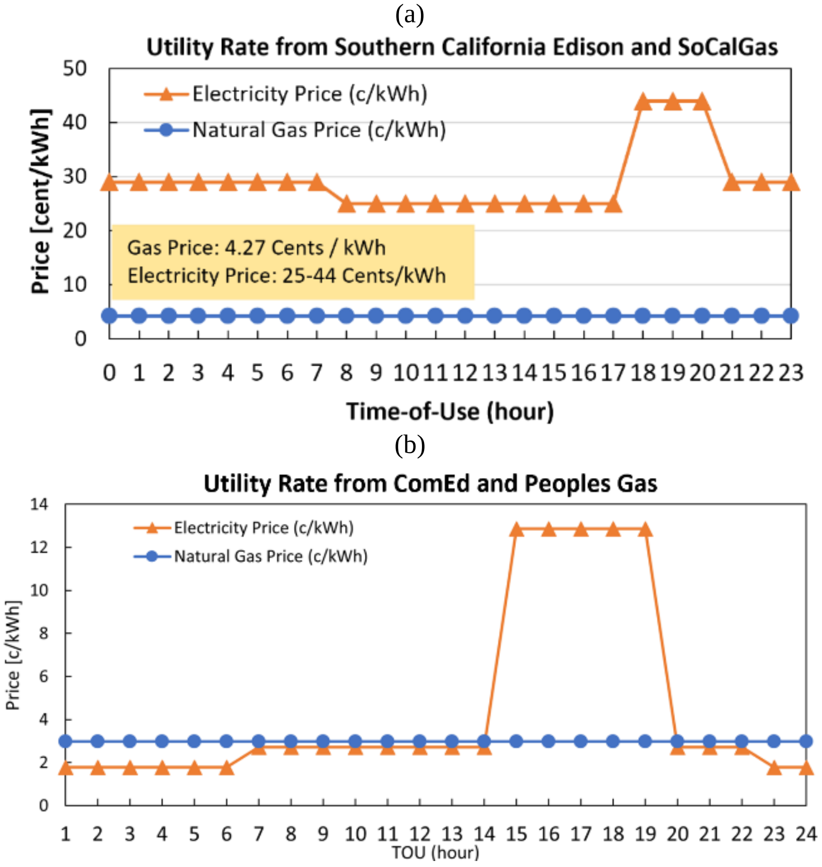

Figure 11: (a) Time-of-Use Utility Rate from Southern California Edison and Gas Price from SoCalGas in Los Angeles; (b) Time-of-Use Utility Rate from ComEd and Gas Price from Peoples Gas in Chicago.

Figure 12 shows the Los Angeles energy usage between electricity and natural gas for various heating systems in a year. For the heat pump (Figure 12 (a)) and the DFHP with conventional control (Figure 12 (c)), electricity is the sole energy source used throughout the year, with consumption peaking during the winter months, indicative of higher heating demand. In contrast, the furnace (Figure 12 (b)) relies exclusively on natural gas, also showing higher usage in the colder months. The DFHP with smart control (Figure 12 d, e, f) shows the versatility of energy source usage, optimizing between electricity and natural gas based on different operational strategies: utility saving, CO_2 reduction, and a balanced mode, respectively. Obviously, the utility-saving mode Figure 12 (d) significantly leverages natural gas during peak months to lower electricity use, while the CO_2 reduction mode (Figure 12 (e)) primarily uses electricity, potentially reflecting a strategy to minimize carbon footprint by relying on a cleaner energy source. The balanced mode (Figure 12 (f)) seems to moderate between electricity and natural gas usage, possibly achieving a compromise between cost and environmental impact. In the smart control modes, the energy consumption patterns reflect active management to align with the specific optimization goals.

Figure 12: Los Angeles Monthly Energy Consumption Breakdown for different heating equipment: (a) Heat Pump; (b) Furnace; (c) DFHP with Conventional Control; (d) DFHP with Smart Control for Utility Saving; (e) DFHP with Smart Control for CO_2 Reduction; (f) DFHP with Smart Control for Balanced Performance between Utility Saving and CO_2 Reduction.

Figure 13 shows the energy consumption monthly breakdown in Chicago. Compared to Los Angeles, the reliance in Chicago on natural gas is prominent, where natural gas consumption is substantially higher than any energy use in Los Angeles, reflecting the colder climate of Chicago. DFHP system with smart control (Figure 13d, e, f) in Chicago exhibit more pronounced seasonal variability, with higher peaks in winter, which contrasts with the more even distribution seen in the Los Angeles case. These peaks demonstrate preferable switching to natural gas during colder months as a response to much higher electricity prices and much lower natural gas prices compared to Los Angeles. The preferable switching to natural gas furnace also attributes to the high emission of heat pump after factoring in its low efficiency under cold weather especially in the scenario of a carbon intensive grid in Chicago. This result suggest that location-specific control strategies are crucial for smart dual fuel heat pump to maintain comfort, reduce energy cost and reduce emission.

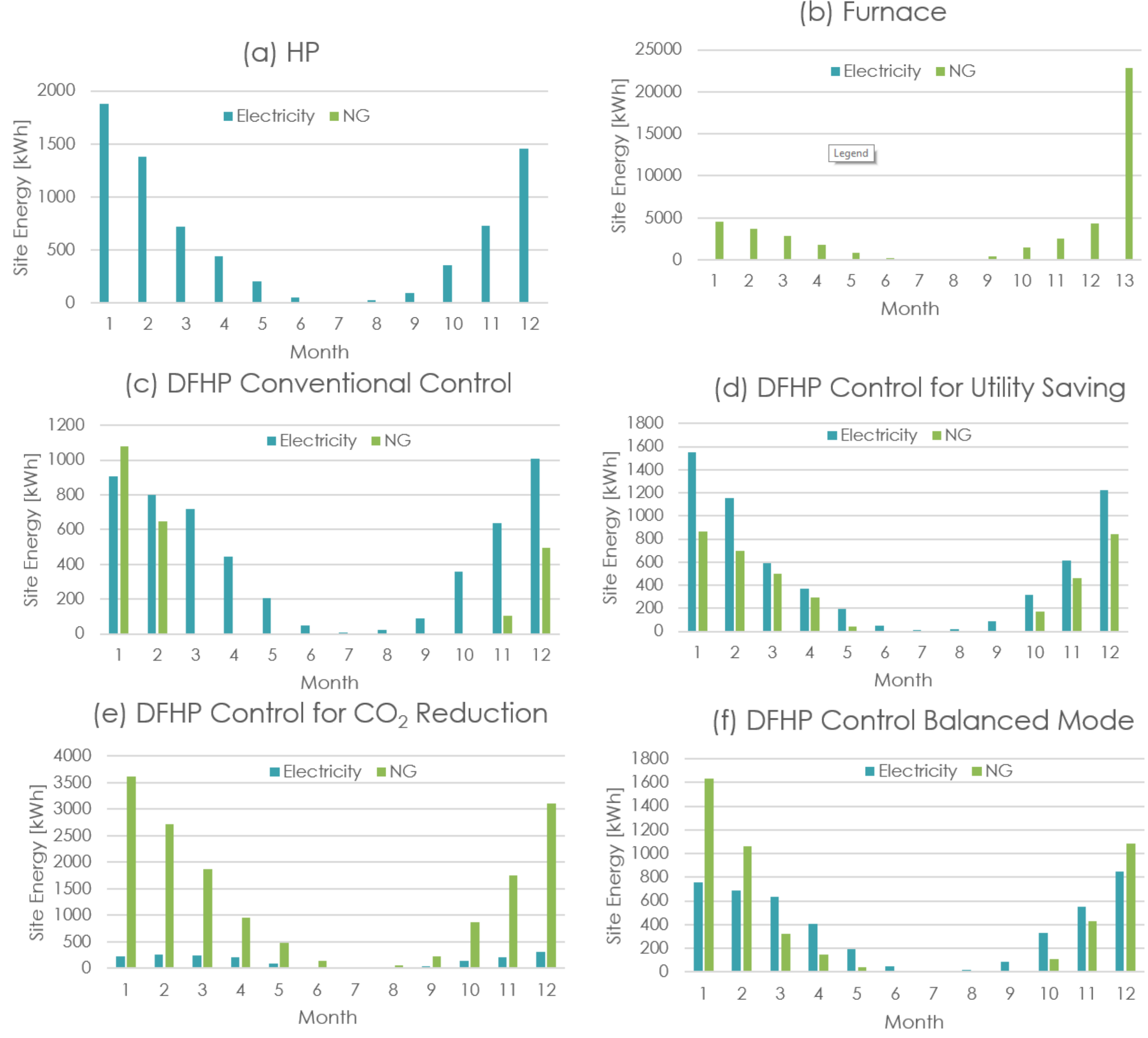

Figure 13: Chicago Monthly Energy Consumption Breakdown for different heating equipment: (a) Heat Pump; (b) Furnace; (c) DFHP with Conventional Control; (d) DFHP with Smart Control for Utility Saving; (e) DFHP with Smart Control for CO2 Reduction; (f) DFHP with Smart Control for Balanced Performance between Utility Saving and CO2 Reduction.

Figure 14 represents a trade-off analysis between annual utility cost and CO_2 emissions for different heating equipment and dual fuel heat pump with different control strategies in Los Angeles. The x-axis displays the annual utility cost, while the y-axis represents the annual CO2 emissions. DFHP with smart control strategies show a spread in the trade-off between cost and emissions. The cost is the cost on the utility bill for the end-users.

In Los Angeles, heat pumps are commonly used HVAC system for space heating. With maximizing utility saving control, DFHP achieves the greatest utility savings of 40.1% compared to the heat pump but at the expense of a 19.6% increase in emissions. With maximizing CO_2 reduction control, DFHP significantly reduces emissions by 14.1% but with less utility cost savings. When DFHP operates under a balanced mode, it offers a compromise between CO_2 reduction and utility saving.

The dash line represents the operation domain of the smart DFHP, indicating the potential range of performance smartly controlled DFHP can achieve. The domain dominates conventional heat pump, furnace and conventional DFHP, it shows that DFHP with smart control can lead to significant utility savings and emission reduction. The preference for the objectives in the control strategy depends on the user's priorities between cost savings and environmental impact.

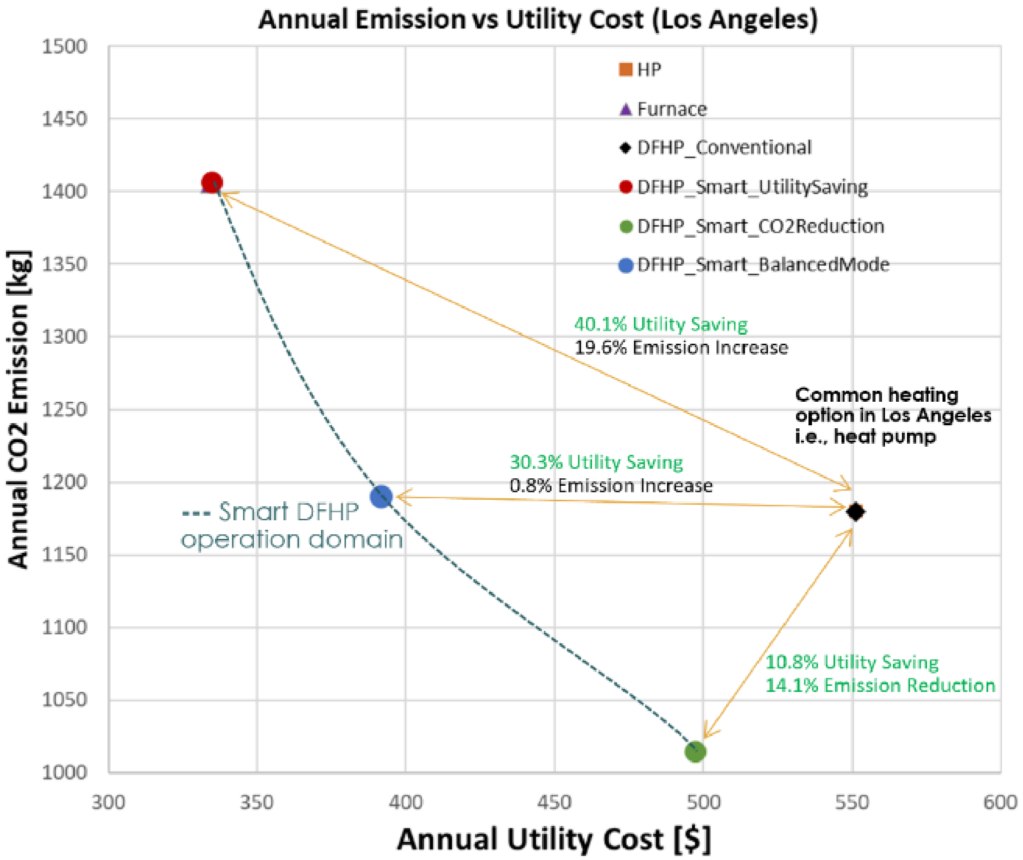

Figure 14: Performance Domain (Emission vs Operation Cost) for Different Heating Equipment in Los Angeles

Figure 15 shows similar comparison between annual utility costs and CO_2 emissions for different heating systems and controls in Chicago.

As can been seen, the emissions are significantly higher across all systems due to the colder climate and more carbon-intensive grid. In Chicago, gas furnaces are commonly used HVAC system for space heating. The DFHP with smart utility saving control achieves a substantial 61.7% utility saving but a 49.8% increase in emissions compared to furnace. It shows a more significant trade-off than seen in Los Angeles. The balanced smart control mode increases emissions by 14.6% but offers a significant utility saving of 58.8%. The emission reduction focused control achieves 8.5% emission reduction with 18.4% utility saving.

The smart DFHP operation domain has a wider spread in Chicago compared in Los Angeles. This implies that in colder climates, the trade-offs between utility savings and emissions are more significant, and the benefits of smart control strategies is more prominent in colder climate and carbon-intensive grid.

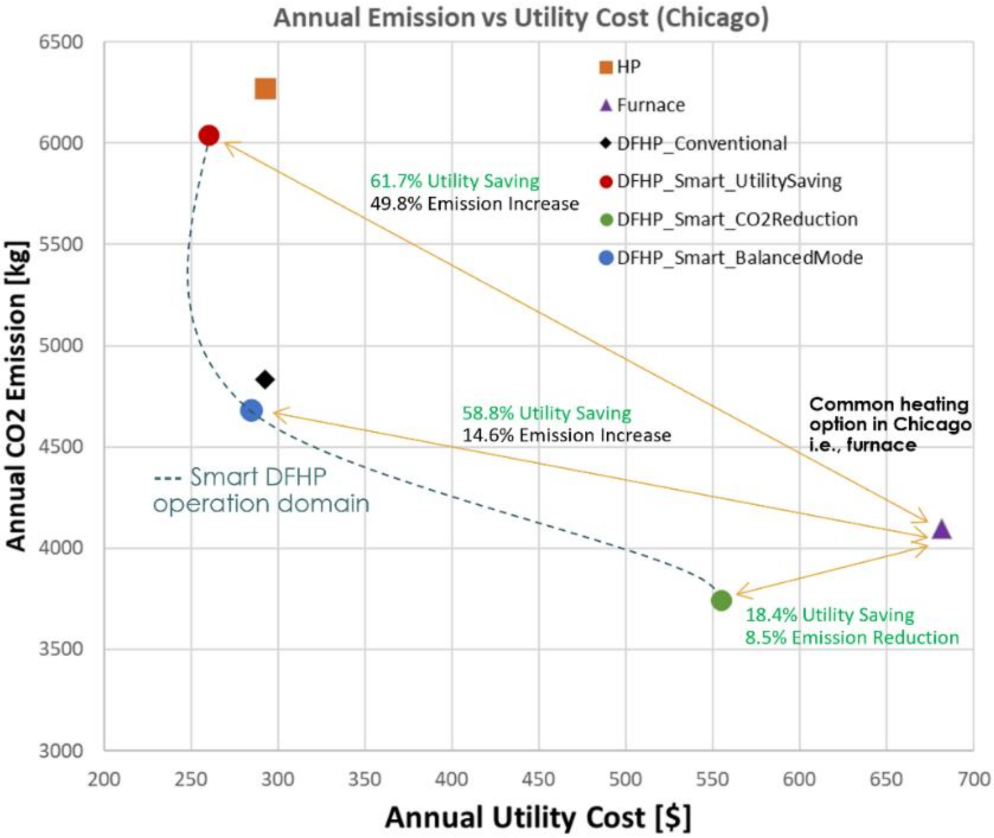

Figure 15: Performance Domain (Emission vs Operation Cost) for Different Heating Equipment in Chicago

Conclusion

The barriers to widespread adoption of conventional heat pump includes high initial investment costs, concerns over the effectiveness in colder climates, and the inertia of homeowners and businesses already invested in existing heating infrastructures. The dual-fuel heat pump allows the system to switch between the heat pump and a fossil fuel furnace, it ensures optimal heating performance even in extreme temperatures. Using the existing furnace will reduce the cost of installation, especially in older homes that could require an upgrade to their electrical service to allow the use of electric resistance heating elements for supplementary heat. However, many existing heating systems lack the intelligent control mechanisms to efficiently manage this switch, leading to sub-optimal energy usage and, in some cases, increased operating costs.

This paper demonstrates the efficacy of a retrofittable dual fuel heat pump controller that allows a heat pump to be added to an existing gas furnace, to accelerate the electrification of space heating. To regulate the operation of DFHP, grid signals including real-time electricity price and gas price, heat pump efficiency, furnace efficiency, and marginal grid emissions are used. Case studies demonstrate significant reductions in peak demand, utility cost, and CO_2 emissions when operated with optimal control strategy: 18.4% utility cost reduction and 8.5% CO_2 emission reduction in Chicago, and 10.8% utility cost reduction and 14.1% CO_2 emission reduction in Los Angeles.

Homeowners can integrate this controller into their current infrastructure, reaping the benefits of a dual-fuel system without the need for a complete overhaul. This enhances the affordability of transitioning to a more sustainable heating solution but also promotes faster adoption rates. Usage of the proposed controller will yield a notable reduction in GHG emissions, assisting in national and global decarbonization efforts. Additionally, it reduces demand on the grid during peak winter months and leads to lower electricity prices and increased grid stability, making the controller an attractive option for demand response programs.

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Disclaimer

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