Energy Modeling and Analysis of Dual Fuel Heating Systems in Single Family Homes

Project Number ET23SWG0005

GAS EMERGING TECHOLOGIES PROGRAM (GET)

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Acknowledgements

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Disclaimer

Abbreviations and Acronyms

Abbreviation and Acronym	Term
ACC	Avoided Cost Calculator
BEM	Building Energy Model
CARB	California Air Resources Board
CET	Cost Effectiveness Tool
CPUC	California Public Utilities Commission
DEER	Database of an Energy Efficiency Resources
EE	Energy Efficiency
GET	Gas Emerging Technology
GHG	Greenhouse Gas Emissions
HVAC	Heating, Ventilation and Air Conditioning
SME	Subject Matter Expert
TOU	Time-of-Use
TRC	Total Resource Cost
TSB	Total System Benefit

Executive Summary

The Gas Emerging Technologies (GET) Program conducted a research study to better understand energy and emissions savings potential of dual fuel heating technology in single family homes of California and provide actionable recommendations. This research will guide utilities, end users, and manufacturers to determine how the dual fuel heating system can maximize both energy savings and carbon emission reductions in the near term.

Project goal: The primary objective of this research is to determine the technical feasibility of dual fuel heating technology for single family homes in California using a combination of EnergyPlus and spreadsheet analysis. The study will analyze the impact of switchover temperature, electric to natural gas rate ratio, and emissions ratios on total energy consumption, costs, and emissions. The research will also determine the cost effectiveness of dual fuel heating technology for single family homes in California using the CEDARS Cost Effectiveness Tool (CET).

Technology description: Dual fuel heating systems contain an electric heat pump paired with a natural gas furnace. In a dual fuel system, the electric heat pump or natural gas furnace is used as a primary source of heat depending upon the fuel prices and weather conditions. Although dual fuel heating systems are already commercially available, they are still considered an emerging technology.

Project methodology: First, the study included SME Interviews, which identified several aspects of dual fuel heating systems, pre-qualification characteristics, comfort characteristics, and control methodologies. Several factors, which play a central role in determining switchover temperature and energy savings, were also identified.

The study also includes a model to analyze dual fuel heating scenarios. The model uses California's Database of Energy Efficiency Resource (DEER) single family building energy models, CZ2022 typical meteorological year weather, marginal utility rates, and marginal emissions factors to isolate heating end-use operating costs and associated emissions. The modeling of different scenarios allowed comparison of the annual emissions and operating cost outcomes across control strategies (switchover temperature and optimal). The results from the model focus on two (2) Title 24 climate zones where installing a dual fuel heating system will be the most advantageous in California.

Project findings: The key findings from this research project are:

- In California, under the studied modeling assumptions, there is not an "economic balance point" wherein the operating cost of the gas furnace would equal the operating cost of the heat pump. In fact, the operating cost of a dual fuel heating system optimized to minimize the emissions is 69%–144% more than a solo gas furnace system.

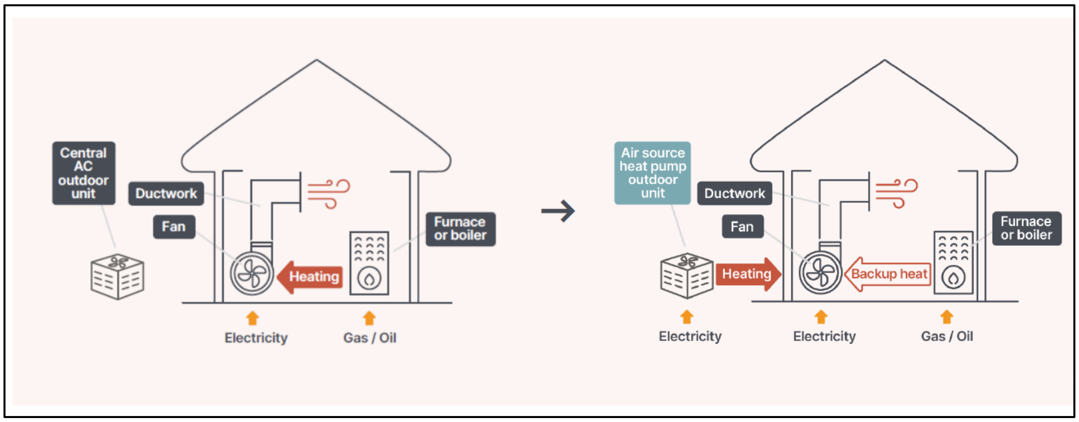
- Likewise, under most of the studied modeling scenarios, there is rarely an "emissions balance point" wherein the greenhouse gas (GHG) emissions from the gas furnace equal the GHG emissions of the heat pump. The emissions savings of a dual fuel system are between 0% - 5% of the emissions from a solo heat pump system and is primarily an electric only scenario.
- SME interviews indicate major barriers in implementing dual fuel heating systems such as lack of sophisticated control methodology and/or innovative thermostats, lack of availability of skilled contractors, lack of information on the systems, and supply chain barriers. However, it was also noted that the adoption of dual fuel heating technology is common in the Northeast and the Mid-Atlantic regions with the federal rebates and easy availability of trained installers.
- The pareto front analysis for total operating costs vs switchover temperature, suggests that as static switchover temperature setpoint increases, the controls approach solo gas furnace operation and as the setpoint decreases, the controls approach solo heat pump operation.
- When single-family homes in climate zones 11 and 16 experience their peak heating load, the emissions are at a secondary peak rather than their primary peak. This is why heat pump operation is usually preferred over gas furnace operation to minimize emissions even at peak heating loads. However, this points to potential future electric grid constraints and changes to the forecasted emissions profile in the winter morning hours as more and more homes in California electrify.
- There is a significant difference in electric and natural gas rates in California for the equivalent net heat output. The current electric gas ratio would need to be reduced by 55% to achieve 100% emissions reduction for CZ 11 with no increase in operating costs.
- The CEDARS Cost Effectiveness Tool (CET) is used to determine the Total System Benefit (TSB) and Total Resource Cost (TRC) for dual fuel heating technology in selected climate zones of California. Based upon the modeling assumptions, the average values of TRC and TSB of CZ 11 are higher than CZ 16. The average values of TRC are 0.6 and 0.5 for CZ 11 and CZ 16 respectively. The average modeled values of TSB are $208.48 and $107.37 for CZ 11 and CZ 16 respectively.

1.0 Introduction: Dual Fuel Heating Systems

Dual fuel heating systems contain an electric heat pump paired with a natural gas furnace and a smart thermostat. These systems offer flexibility to run the heating component (heat pump or a furnace) that is most cost and emissions effective under the weather and/or grid conditions at a given time. In a dual fuel system, the electric heat pump or natural gas furnace is used as a primary source of heat depending upon the fuel prices and weather conditions. By reducing the number of hours that the furnace operates when conditions permit a heat pump to run efficiently and take advantage of grid electricity from clean sources, the dual fuel heating system may reduce the annual GHG emissions. Conversely, by operating the gas furnace at the coldest hours of the year or during the peak electric demand periods (thereby avoiding grid electricity from generation sources with potentially greater emissions), the dual fuel heating system may reduce operating costs and may reduce annual GHG emissions and/or electric peak demand. In a home with an existing gas furnace and central AC, the conversion to a dual fuel heating system leaves the natural gas furnace connected to the natural gas supply grid. The dual fuel heating system provides a unique opportunity to use both natural gas and electric heat pump systems when they are best suited to heat the space in terms of lowest cost and/or GHG emissions.

Figure 1 illustrates a schematic of central AC replacement by a heat pump. The heat pump uses the same ducts as the AC and provides cooling in summer and heating in winter. The gas furnace uses the same duct work when the heat pump is shut off.

Figure 1: Illustration of central AC replacement by a heat pump [1]



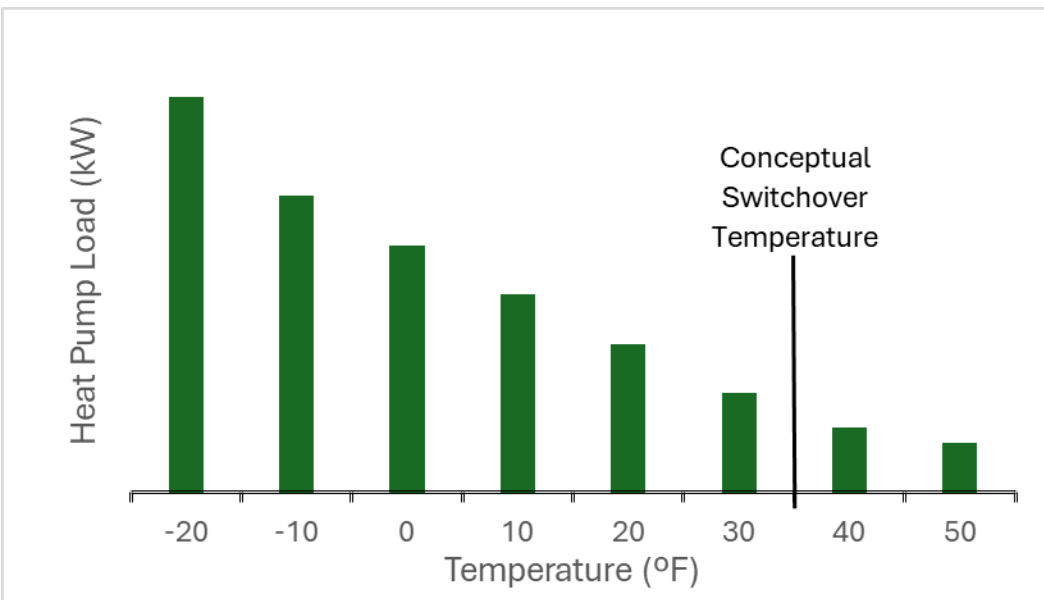
Dual fuel heating systems can be implemented in a variety of configurations.

a. Replacement of air conditioner with an electric heat pump and a controller to work with an existing central furnace.
b. Central split system with replacement of existing central furnace with a more efficient one and the installation of new heat pump and a controller.

c. Installation of a single or integrated packaged system that has the heat pump and natural gas furnace contained in a single housing along with a smart thermostat.

Switchover temperature is a key factor which determines the potential energy and emissions savings of dual fuel heating systems. A switchover temperature is the outdoor air temperature at which the operation of electric heat pump switches to natural gas furnace or vice versa when heating is needed. This switchover temperature can be based on outdoor air temperature, capacity constraints, pricing, and emission signals. Figure 2 illustrates how a heat pump with the same rated capacity performs differently as outdoor air temperature decreases. The heat output rate and efficiency of heat transfer decrease for lower ambient temperatures. If the heat pump is oversized to meet the demand at lower temperatures, this would lead to compressor cycling during the frequent moderate cold temperatures and consequently less efficient performance. To avoid this problem, the heat pump is typically sized to meet the cooling load and to deliver a portion of the home's heating load at the design temperatures. The home can rely on supplemental heat (such as natural gas) at the lowest ambient temperatures. Dual fuel heating systems with a properly set switchover temperature can avoid electric heating demand during winter peaks [2].

Figure 2: Prototypical Switchover temperature in dual fuel heating scenarios



The heating capacity of a heat pump drops as outdoor air temperatures drop. The 'capacity balance point' represents the outdoor air temperature when the rate of heat loss from the home equals the maximum rate of heat the heat pump can provide. Like heating capacity, the energy efficiency of a heat pump drops as outdoor air temperature decreases. The 'economic balance point' describes the outdoor air temperature at which the operation of natural gas furnace would yield the same operating cost as the heat pump.

2.0 Background: Housing Stock Characteristics in U.S. and California

This section provides the background information on housing stock characteristics in the U.S. and California. Several project reports and previous studies were reviewed to gain insights on housing stock and fuel consumption characteristics of California. In the U.S., space heating accounts for 43% of residential energy usage and 27% of residential CO_2 emissions [1]. Table 1 summarizes the main fuels and equipment in U.S. households. About 47% of the homes are good candidates for retrofit of an existing AC with a heat pump, because they have pre-existing centralized ducts.

Table 1: Summary of U.S. Residential heating systems by fuel and type, 2015 [1]

MAIN FUEL/HEATING METHOD	DUCTED SYSTEM (FURNACE, CENTRAL HEAT PUMP)	NON-DUCTED SYSTEM (BOILER, RADIATORS, BASEBOARD HEATERS, SPACE HEATERS, MINI-SPLIT HEAT PUMPS)	TOTAL HOMES WITH GIVEN FUEL	HOMES WITH GIVEN FUEL AND ONE-WAY CENTRAL AC (CANDIDATES FOR AC TO HP SWAP)
Methane Gas	39%	9%	**49%**	**29%**
Oil	3%	2%	**5%**	**1%**
Propane	3%	1%	**4%**	**2%**
Electric Resistance	14%	11%	**25%**	**12%**
Electric Heat Pump	9%	1%	**10%**	**NA**
Wood	0%	3%	**3%**	**0%**
Other	0%	0%	**0%**	**0%**
None	NA	NA	**4%**	**1%**
Total	**68%**	**28%**	**100%**	**47%**

According to a report by CLASP, a leading global authority on efficient appliances' role in fighting climate change, about 32% of the households in California are equipped with natural gas heating and central AC and are ready for implementing dual fuel heating systems [1]. See Table 2.

Table 2: Households ready for dual fuel heating, California (2018) [1]

Number of households in California	% equipped with natural gas heating and central AC
12,717,801	32% (4,059,267)

According to the 2020 Residential Energy Consumption Survey (RECS), about 57% of the total housing units in California are single family detached homes [3]. About 62% of the homes are equipped with natural gas furnaces as the primary heating equipment. See Tables 3 and 4 for further details.

Table 3: Structural characteristics of U.S. homes- California (2020) [3]

Number of total homes in California	13.18 million
% of Single-family detached homes	57%
Number of Single-family detached homes	7.58 million

Table 4: Space heating characteristics of U.S. homes- California (2020) [3]

Number of total homes in California	13.18 million
% homes with natural gas furnace as main heating equipment	62% (8.2 million)
% homes with central heat pump as main heating equipment	3% (0.41 million)
% homes with steam or hot water boiler as main heating equipment	1% (0.12 million)
% homes equipped with secondary heating equipment	36% (4.74 million)
% all-electric homes	8% (1.03 million)

The key findings from the 2019 California Residential Appliance Saturation Study (2019 RASS) were studied to determine the housing stock and fuel characteristics [4]. The saturations of fuel type by major household end usage are presented in Figure 3. Space heating systems are fueled primarily by natural gas for about 63% households in the study. Figure 4 illustrates that natural gas space heating is more common in single family homes compared to other dwelling types.

Figure 3: Combined electric, natural gas, and other fuel saturations [4]

(Note: In Figures 3 and 4, the x-axis is % of households.)

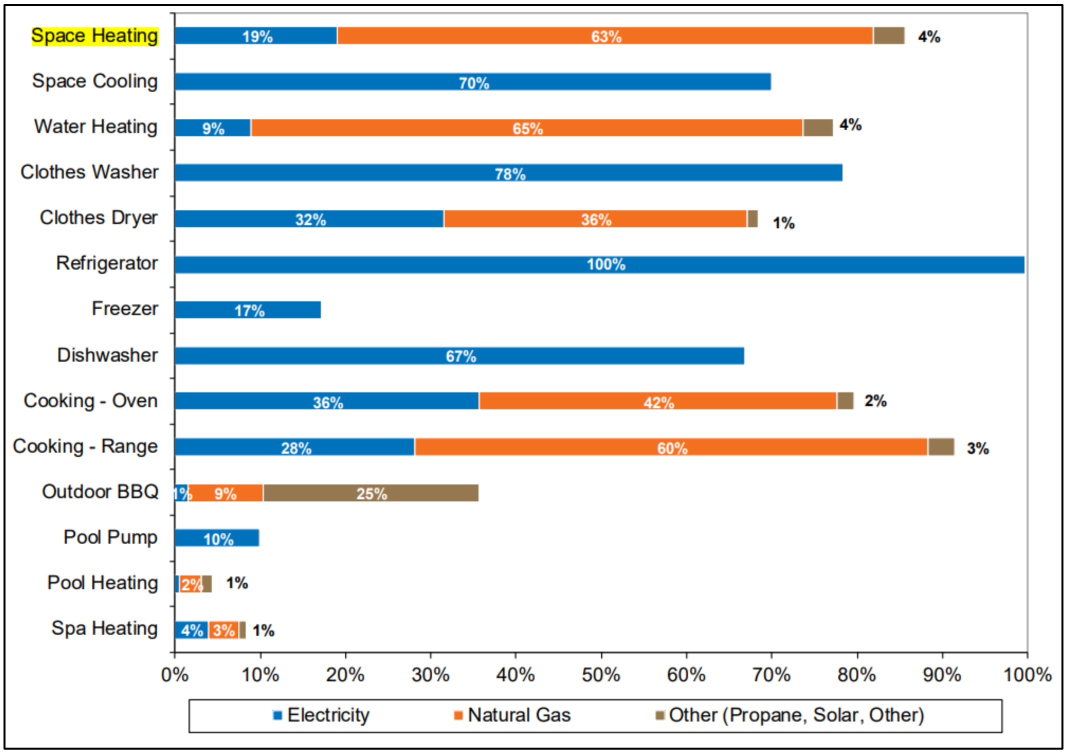
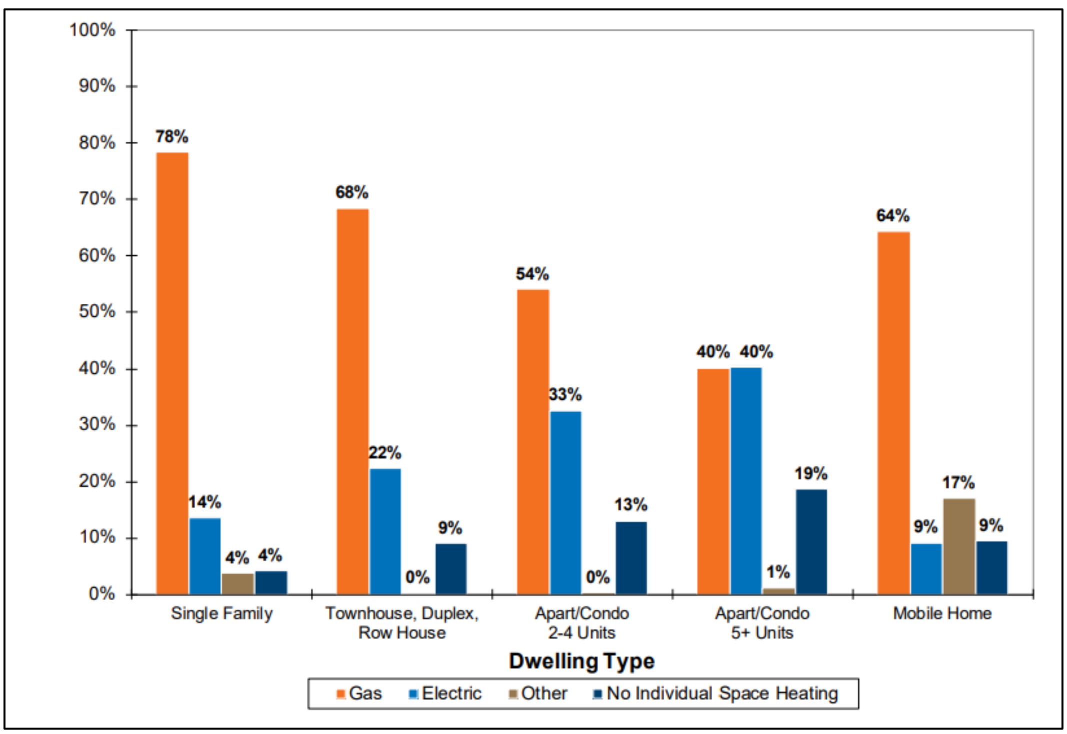


Figure 4: Space heating fuel by dwelling type [4]



3.0 Assessment Objectives

The objectives of conducting this research study on dual fuel heating systems are listed below.

a) The primary objective of this research is to determine the technical feasibility of dual fuel heating technology for single family homes using EnergyPlus and spreadsheet analysis of modified DEER single family energy models.
b) The study involves up to five (5) SME Interviews to gather more information about pre-qualification for installing dual fuel heating systems, barriers and lessons learned from previous research projects or pilot programs.
c) The current cost effectiveness of such dual fuel heating systems is unknown. This research aims to determine the potential cost effectiveness of installing a dual fuel heating system in California, based on the TRC and TSB tests.
d) The modeling of different scenarios along with the spreadsheet analysis analyzes the impact of switchover temperature on total energy consumption and operating costs. Additionally, this involves optimization of the switchover temperature for minimum annual site fuel usage, total operating costs, and source GHG emissions respectively using the modified DEER prototype models.
e) The analysis also examines the interplay between heating loads and emission factors hourly load profiles for each selected climate zone.

Note: Since the simulation results did not show an 'economic balance point' or 'emissions balance point' as expected, additional analysis was undertaken to examine at what gas-electric cost ratio would there be an emissions balance point. Additionally, the impact of gas-electric ratio and carbon emissions credit on overall customer operating costs for a dual fuel heating system was examined. Note that section 4 and 5 highlight the key findings from previous studies and section 6 onwards explain the methodology and key results from this ET study.

3.1 Expected Outcomes

a) Determine the two Title 24 climate zones where installing a dual fuel heating system will be the most advantageous (from initial modeling setup and analysis)
b) Summary of pre-qualifications or site characteristics required for installing dual fuel heating systems, control strategies and estimated retrofit costs.
c) Summary of lessons learned from the pilot studies or implemented Energy Efficiency programs in other states and countries.
d) Qualitative comparison between dual heating and all electric systems based on IAQ, comfort and maintenance costs.

e) Optimization of switch over temperature for minimized annual fuel costs and usage, GHG emissions.

f) Cost effectiveness evaluation of dual fuel heating systems (TRC/TSB) in the selected climate zones.

4.0 Literature Review

Several organizations have undertaken dual fuel heating research projects and below is a summary of the findings from those previous studies.

a) NEEA Study - Dual Fuel Heat Pump Market Research

The Northwest Energy Efficiency Alliance (NEEA) and its Natural Gas Team published a market research study on dual fuel heating and gas heat pump heating in residential and commercial markets in June 2023 [5]. The study highlighted that market demand exists for dual fuel heating systems.

The key insights for dual fuel heating in the studied residential market (Pacific northwest) are as follows:

1. Market demand exists for both dual fuel and gas heat pumps but there is a stronger opportunity for dual fuel heating.
2. The growing desire for cooling capability and growing social interest in carbon footprint reduction combined drive interest in dual fuel technology in the residential sector.
3. Energy efficiency and carbon footprint reduction are considered to be important by buyers and both technologies (dual fuel heating and gas absorption heating) satisfy these desires.
4. Residential buyers are driven by comfort levels in the home and reduced HVAC fuel costs. Many are also conscious of the carbon footprint of their HVAC system.

The following is a summary of barriers to adoption of dual fuel heat pump technologies in residential applications from this study:

1. Lack of awareness about technology.
2. The residential buyers assume newer HVAC technology will incur higher upfront costs.
3. Some residential buyers express concern over the reliability of dual fuel heating systems and physical footprint of dual fuel heat pumps.
4. Unfamiliarity or unfavorable prior installation experience with HVAC contractors.

Recommendations to overcome barriers in the residential market are as follows:

1. Promote fuel cost savings and provide head-to-head comparisons of dual fuel heating and competitive technologies.
2. Encourage partners to provide physical footprint requirements for dual fuel systems.

b) GTI Study - Assessment of Natural Gas Decarbonization Pathways in Colorado Residential Sector

Gas Technology Institute (GTI) published a report for Black Hills Energy on available and emerging technology pathways for reduction of greenhouse gas emissions in Colorado's residential sector [6]. The report discusses dual fuel heating technology as one of the emerging technology pathways. Complementing electric heat pumps with natural gas furnaces is a cost-effective peak shaving approach that helps avoid electric grid sizing impacts[1] during very cold periods. The modeling of a 1,660 sq. ft. Colorado home demonstrated that a dual fuel heating system results in lower peak electricity usage. The report also notes the reasons behind national consumer preferences for space heating with natural gas compared to electric:

1. Beyond the cost effectiveness, consumers prefer natural gas because of its performance advantages.
2. Homes heated with natural gas offer better indoor comfort because they deliver higher air temperatures and space heating set points are met more quickly as compared to electric heat pumps.

This study recommends gas and electric EE programs to take following steps:

1. Natural gas EE programs: retain/use high efficiency gas furnaces.
2. Natural gas and electric EE programs: Invest in home/building envelope improvements to lower space conditioning loads. Invest in research and development of smart thermostats that choose electric or gas space heating depending on outdoor temperature, operating costs, and other parameters.
3. Electric EE programs: Replacement of air conditioners with electric heat pumps.

c) Dual Fuel Air - Source Heat Pump Monitoring Report, Michigan

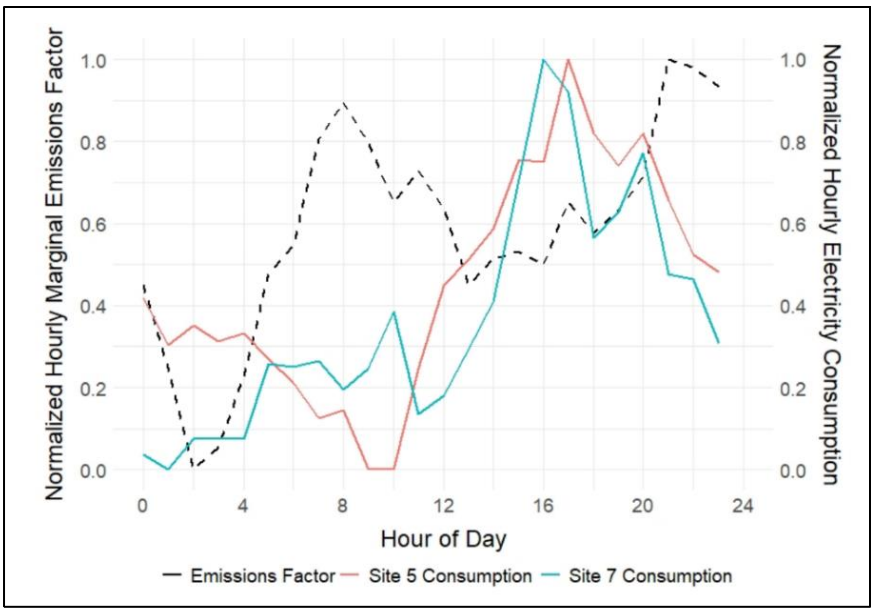
The Michigan Electric Cooperative Association (MECA) Energy Optimization (EO) Program's heat pump pilot monitored the performance of eight (8) residential, centrally ducted, dual fuel air source heat pumps [7]. The study selected sites with a variety of heat pumps—single speed, variable speed and multi-speed systems backed up with propane furnaces.

[1] The electric grid would have to be upsized to accommodate new demands from electrification of heating.

This study calculated the average coefficient of performance (COP) and emissions savings over the study period for the installed dual fuel heating system vs. the standard gas furnace and AC unit. Emissions savings varied from 5% to 16%.

The study deliberately selected sites with a variety of heat pumps: four of the households had variable speed systems, two had multi-speed systems, and two had single-speed systems. The heat pumps at two sites did not have a configured switchover temperature. Site 5 did not have a configured switchover temperature and Site 7 had switchover temperature of 20^{0} F. Site 5 had installed a two-speed heat pump and Site 7 had installed one-speed heat pump. In this study, Site 5 had more emissions savings than Site 7. Figure 5 explains this by showing how site 5 used less electricity during periods of the day where the grid is "dirtier" (hours 5-10) and more electricity when the grid is "cleaner" (hours 0-4). The time varying trends revealed the opportunities to decrease usage of heat pumps during high emissions periods and increase heat pump energy consumption during low emissions periods.

Figure 5: Coincidence of hourly electricity consumption and emissions factor. [7]



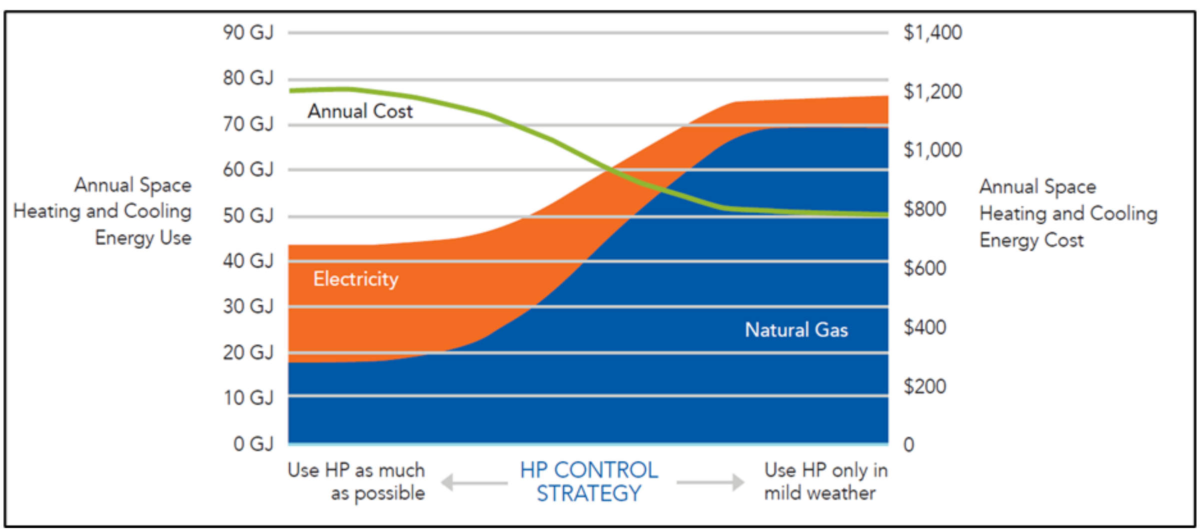
Performance of dual fuel heat pumps in the study varies based on many factors including switchover temperature, system sizing, efficiency levels of equipment and type of rate structure-tiered or time-of-use (TOU based). The energy savings will be maximized with a high efficiency, variable speed heat pump that is sized and configured to operate at low temperatures. Low temperature operation often means the capacity of the heat pump is increased so it can provide enough heating during colder temperatures. The size of heat pump is an important discussion point between the HVAC contractor and homeowner before installing a dual fuel heat pump because it will impact the switchover temperature, upfront costs, and expected energy savings. However, the heat pump is typically designed to deliver a portion of home's heating load at design temperatures and rely on supplemental heat at the lowest outdoor air temperatures.

d) Enbridge Gas - Canada

This report compares the economic, electrical demand and GHG reduction potential of full-electric heat pump- gas dual fuel and cold climate electric heat pump-gas dual fuel systems [8]. The results demonstrate the lifecycle costs of dual fuel heating systems are higher than the baseline natural gas heating systems but lower than the full-electric heating systems. The report indicates that smart controls and operational strategies for dual fuel heating, as well as the development of targeted Time-of use (TOU) pricing can help deliver the full benefits to the customers.

Figure 6 illustrates the impact of control strategies on total energy usage and operating costs. At a lower switchover temperature, the electricity usage of the heat pump is maximized, but the total operating costs are higher when the electric heat pump usage is maximized versus when it is only used in mild weather conditions. Likewise, the operating cost is lower when the switchover temperature is higher to use the electric heat pump only in mild weather, but the total annual energy use is higher. The maximum benefit to the customer lies somewhere in the middle of these two extremes. The average off peak electricity rate in Ontario is 9.7 Canadian cents per kWh consumed (based on rates effective November 2017).

Figure 6: Control strategies Impacts on dual fuel heating system [8]



This study modeled a cloud based smart dual fuel switching system (SDFSS) of a residential dual fuel system of electric heat pump and natural gas furnace [9]. The fuel switching algorithm (i.e., the algorithm deciding whether natural gas furnace or electric heat pump will operate at a specific time), accounts for the following factors:

1. TOU based electricity pricing.
2. Natural gas pricing.
3. Outdoor air temperature.
4. Capacity and COP of electric ASHP derived from the manufacturer's data based on current outdoor air temperature.
5. Efficiency of natural gas furnace (not sensitive to outdoor temperature).
6. GHG emissions factors for electricity and natural gas.

The SDFSS algorithm is iterated on an hourly basis. The algorithm has an hourly decision mechanism which selects the fuel source to be operated based on the hourly costs of each alternative. Note that this analysis is like the approach of this ET study.

e) ComEd Energy Efficiency Program

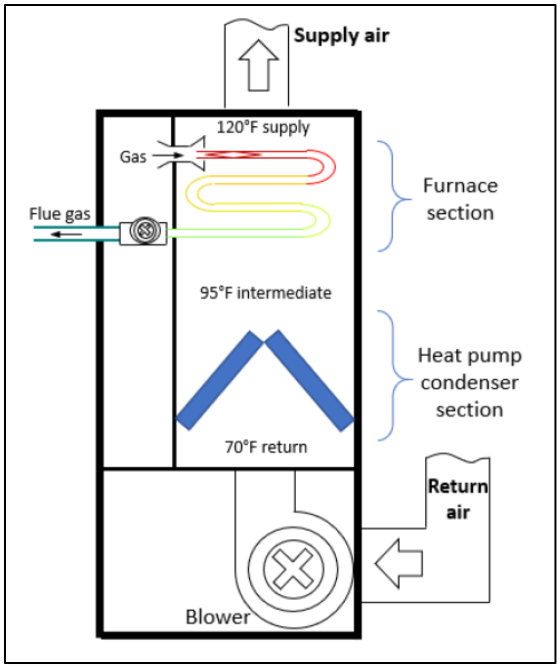
ComEd has published a guide for best practices in the installation of electric heat pumps. Proper installation of an electric heat pump is necessary to ensure customer satisfaction and efficient operation. Listed below are the best installation practices and tips to prevent common installation issues from this ComEd resource: [10]

1. Free flow of air is a must- follow manufacturer clearance requirements from obstructions, this includes walls, overhangs, and other outdoor units etc.
2. Location of outdoor units must be approved by homeowners.
3. Ensure adequate clearance above historical average maximum snow depth.
4. When installing central ASHPs using existing ducts, always ensure that ductwork is adequately sized for heat pump air flow requirements and available static pressure.
5. Ensure a compatible thermostat is installed with ASHP.

f) Simultaneous operation of electric heat pump and natural gas furnace

Zhenning Li, et. al. at Oak Ridge National Laboratory, developed a novel dual fuel heat pump system for space heating of residential and small commercial buildings [11]. As discussed earlier in this report, the conventional dual fuel heating systems either run on natural gas or electricity at any given moment. However, the proposed technology in this study, the Seamlessly Fuel Flexible Heat Pump (SFFHP), consumes natural gas and electricity simultaneously for heating with built-in optimization. Figure 7 demonstrates a schematic diagram of SFFHP. The process air is heated across the heat pump condenser first and then across the furnace coils. SFFHP uses a modular communication interface to adjust the capacities of the electric heat pump and a gas furnace continuously. This results in energy savings by allowing each subsystem to operate where it performs best by utilizing the optimized combination of natural gas and electricity.

Figure 7: Schematic Diagram of Seamlessly Fuel Flexible Heat Pump (SFFHP) [11]



The output of the electric heat pump and gas furnace are adjusted continuously based on ambient temperature, utility price signals and marginal grid emission signals. An optimal Model Predictive Control (MPC) strategy was devised with the objective of minimizing CO_2 emissions and utility costs. MPC was used to adjust the capacity of electric heat pump and natural gas furnace.

The MPC uses several parameters such as weather data, natural gas and electricity pricing signals, marginal emission rates of grid electricity, and equipment performance data. Figure 8 depicts a schematic of MPC architecture. In this paper, the information stream of emissions rates of grid electricity is based on a calculation methodology developed by a manufacturer X. Manufacturer X's proprietary model calculates Marginal Operating Emissions Rates (MOER) in real time, every 5 minutes using a combination of grid data from the respective independent system operator (ISO) and historical data of continuous emissions monitoring system.

Figure 8: Optimal model-based control architecture of SFFHP [11]

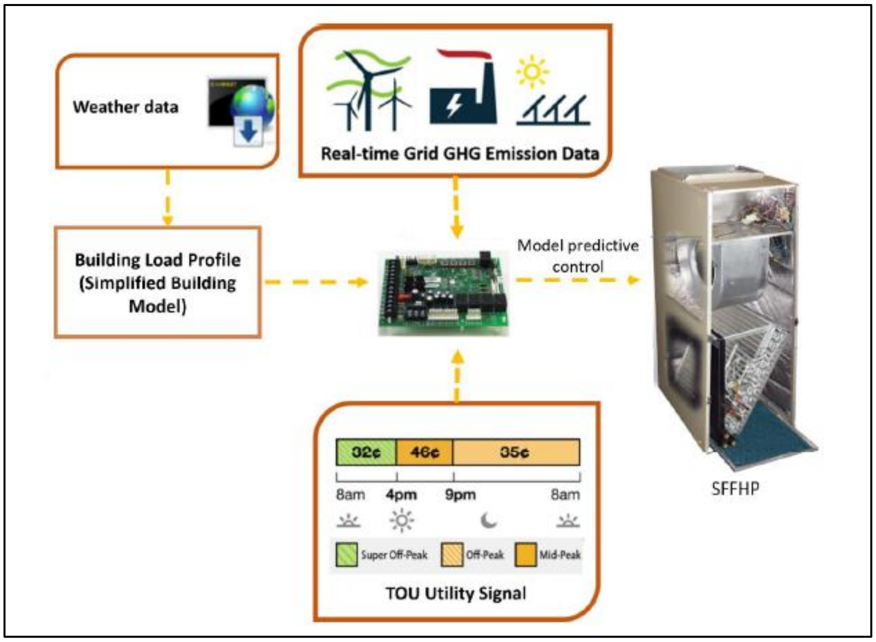
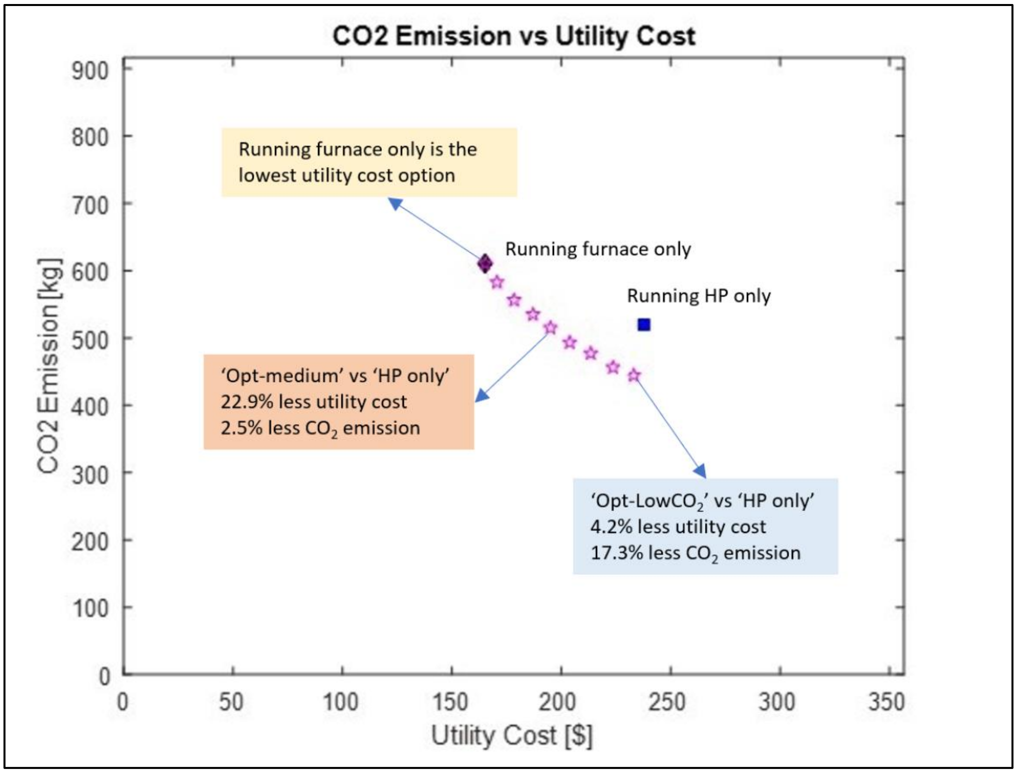


Figure 9 shows the pareto front for the optimal performance of SFFHP operated under the MPC strategy. Different performance points represent different operation strategies for SFFHP by varying the weights on the two objectives: emission reduction and operation cost reduction. As indicated by the pareto front, running the natural gas furnace alone is the cheapest option due to the significantly lower gas price. 'Opt-medium' is in the middle of pareto front, and it has compromised performance between utility savings and emission reduction. Whereas 'Opt-LowCO_2' yields the most significant CO_2 emission reduction. Compared with a conventional heat pump, when SFFHP is operated under 'Opt-medium' control strategy, it yields 22.9% utility cost savings with only 2.5% less CO_2 emissions. When operated under 'Opt-LowCO_2' strategy, it yields 4.2% utility cost reduction and 17.3% CO_2 emissions reduction compared with the electric heat pump.

Figure 9: Pareto front for SFFHP - optimal control strategies [11]



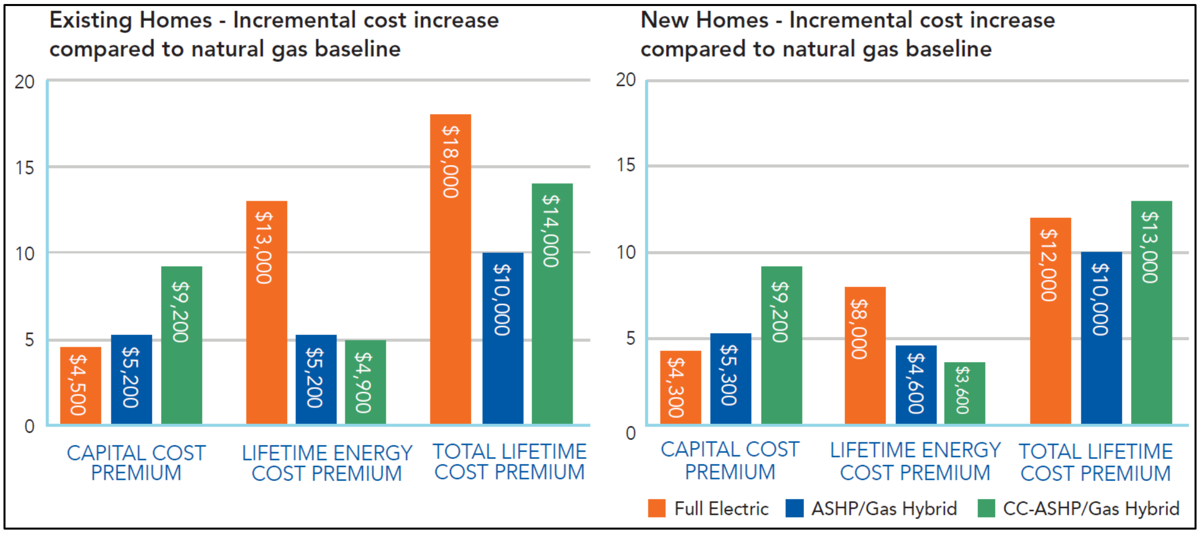
4.1 Summary on measure cost of dual fuel heat pump

The information on measure cost or incremental cost of a dual fuel heat pump for an average home with 3-ton capacity was compiled from different sources.

According to a report by CLASP (2022), the market price of a non-cold climate heat pump is $1,000-$2,000 more than an equivalent AC. The total installed cost for a replacement 15 SEER AC is $1,700-$3,000 versus $2,000-$4,300 for an equivalent heat pump [1]. This paper is an extension and refinement of CLASP's 2021 dual fuel heat homes analysis.

The Advanced Energy Centre (AEC) and Enbridge Gas published a report which compares the economic, electrical demand and GHG reducing performance of different electrification options-all using electric heat pumps in both retrofit and new homes in Ontario. According to the report, the capital and total lifecycle costs of dual fuel heating systems are lower than full electric systems [9]. Figure 10 shows the comparison of incremental and total lifecycle costs of dual fuel heating systems to natural gas systems for 3-5 tons heat pumps capacity ranges. Note that the costs are listed in Canadian dollars and CC-ASHP stands for cold climate air source heat pumps.

Figure 10: Comparison of incremental and total lifecycle costs [8]



4.1.1 Dual Fuel Air-Source Heat Pump Monitoring Report, Michigan

The aforementioned Dual Fuel Air-Source Heat Pump Monitoring Report by MECA also collected and reported on dual fuel heat pump costs [7]. The report calculated the annual cost savings at each site where a dual fuel heat pump was installed and estimated the incremental cost of installing a dual fuel heat pump over a 96% efficient gas furnace and a SEER 14 AC unit. The incremental costs were estimated using a cost database from the National Renewable Energy Laboratory (NREL). The NREL costs are average costs and were not exactly representative of each site's actual installation. The study authors also interviewed HVAC contractors about dual fuel material costs and found that those market actors estimated that a dual fuel heat pump's incremental cost (scenario of replacing air conditioner with a heat pump) typically ranges from $1,000-$4,000/ton in MCEA's territory. The study applied a 30% cost premium to sites with 5-stage and variable-speed heat pumps to account for more expensive components at those sites and the HVAC contractor cost intuition findings. Table 5 shows the incremental costs, annual energy cost savings, and payback period for each site in the MCEA study.

Table 5: Incremental costs and payback periods [7]

Site	Incremental Cost	Annual Cost Savings	Simple Payback Period
1	$2,564	$811	4 years
2	$3,214	$678	5 years
3	$2,412	$273	9 years
4	$2,585	$1,085	3 years
5	$900	$576	2 years
6	$2,022	$308	7 years
7	$700	$299	3 years
8	$600	$603	1 year
Average	$1,875	$579	4 years

If a 15-year effective-useful life is assumed for a dual fuel heating system, Table 5 shows that these systems payback within their effective useful life. However, the average full cost of installing a new dual fuel heating system was $10,381, which is still a large upfront cost for some customers and its importance should not be underestimated.

4.1.2 Information about measure cost of dual fuel heat pump from other sources

CostHelper website offers cost information about a variety of products and services. According to CostHelper report, adding a dual fuel heat pump to an existing natural gas ducted system typically costs $2,500-$5,500 for just the electric ASHP in an average home (for 3-ton capacity and AC retrofit scenario) [12]. Installing a completely new dual fuel system with both electric ASHP and natural gas furnace can cost around $6,000-$10,000 or more. Installing or replacing ductwork typically costs about $35-$55 a linear foot for labor and materials, or $1,000-$5,000 more for an average home.

Table 6 illustrates the summary of incremental costs of dual fuel heat pumps for different scenarios and configurations, with cost ranges compiled from different sources.

Table 6: Summary table of incremental costs of dual fuel heat pumps [7, 12, 13]

Scenario	Description	Cost range
Adding electric heat pump to an existing natural gas ducted system	3-tons capacity, AC retrofit case	$1,000-$5,500 (Add 30% cost premium for multi-stage and variable speed heat pump cases)
Installing new dual fuel system with both electric heat pump and natural gas furnace with existing usable ductwork	3-tons capacity heat pump with new 80% efficient natural gas furnace	$6,000-$13,000
Installing new dual fuel system with both electric heat pump and natural gas furnace with existing usable ductwork	3-tons capacity heat pump with 97% efficient communicating natural gas furnace	$16,000-$19,000
Common additional: duct improvement, cleaning, and sealing		$1,000-$5,000 ($35-$55 a linear foot for labor and materials)
Common additional: upgrading the electric panel to 200 Amps		$1,300-$3,000

Note: These cost ranges are before any rebates. Dual fuel heating systems are currently eligible for up to $2,600 in federal tax credits [12].

5.0 Findings from Subject Matter Expert (SME) Interviews

This study included Subject Matter Expert (SME) interviews to gain insights on several aspects of dual fuel heating systems, pre-qualification characteristics, control methodologies, range of incremental costs and comfort characteristics. Nine (9) stakeholders (thermostat and dual fuel packaged system manufacturers, utilities, researchers in controls, energy, and HVAC domain) were interviewed during May-June 2023. The response rate is summarized in Table 7. As indicated, a response rate of 82% and participation rate of 100% was recorded. See Appendix A1 for the interview questionnaire.

Table 7: Organization Response Rate

Number of organizations contacted	Number of organizations that responded	Actual participation	Response rate	Participation rate
11	9	9	82%	100%

This sub-section summarizes key findings from the SME interviews. Following are the major barriers in implementing dual fuel heating systems:

1. Lack of sophisticated control methodology or innovative thermostats, unknown customer level of controls usage, and customer demand.
2. Lack of availability of skilled contractors (experience in installing dual fuel heating systems).
3. Information barrier- the necessity of training customers and customers
4. Supply chain barrier- shortage of electric ASHPs in the market.
5. Differences in perceived comfort- Perceived comfort can influence customer behavior. Achieving the savings and payback requires customers to avoid disabling the controls.

Following are the good installation practices of dual fuel heating systems:

1. Installing outdoor units on a raised platform above average snowfall depth (where applicable).
2. Following manufacturer clearance requirements from obstructions- free flow of air is a must.
3. Outdoor locations need to be chosen with extreme attention to detail as well. Outdoor noise disturbances and code requirements must be reviewed.
4. Appropriate selection of communicating thermostat and associated controls.

5. When installing centrally ducted electric heat pumps using existing ducts, it is recommended to always ensure ductwork is adequately sized for heat pump airflow requirements and available static pressure.

Following are some of the pre-qualifications required for the installation of dual fuel heat pumps:

1. Visual inspection of ductwork.
2. System configuration changes for thermostat wiring changes (low voltage wiring).
3. Determine if there is room for added electrical load in the breaker box.
4. Identified location for an outdoor condenser.
5. Weatherization of the home is ideal but not a mandatory requirement.

Following are the parameters that affect the switchover temperature:

1. Outside air temperature - affects the capacity and efficiency of electric heat pump.
2. Manufacturing specifications of ASHP and natural gas furnace.
3. Local utility rates- electric and natural gas.
4. Grid emissions data.
5. Setpoint conditions and heating/cooling setback temperature.

6.0 System Simulation Model and Methodology

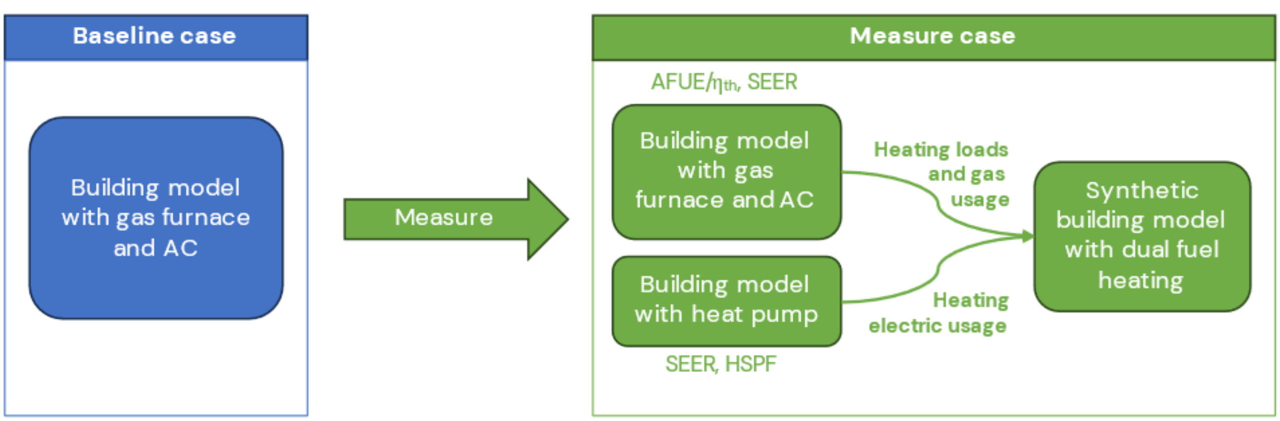
6.1 Building Energy Model and Assumptions

This section summarizes the properties of building energy model (BEM), data sources and the assumptions behind analysis. The goal of this task was to select two models: one gas furnace model and one electric heat pump model to simulate the dual fuel heating system.

For the evaluation of the energy usage and performance of the dual fuel heating system, there are two fundamental types of analysis: measure analysis and measure case optimization. The goal of model selection is to develop a set of building energy models that meet the needs of measure analysis and measure case optimization, drawing on existing sources for calibrated building energy models and applying modifications as needed to address aspects of the dual fuel heating system measure that differ from the applications in which the models were previously utilized. The incremental cost and payback are also based on this analysis framework.

In the nomenclature of energy efficiency projects, a measure is the action to upgrade from a baseline technology to a measure case technology and the energy savings attributed to the measure are the difference in usage between the baseline case and measure case. In this context of dual fuel heating systems, the baseline technology is an HVAC system consisting of a gas furnace and air conditioning components with a basic controller. The measure case technology is a dual fuel heating system which is an HVAC system consisting of a gas furnace, air source heat pump, and an advanced system controller. Figure 11 illustrates the combined system which is then synthesized from these models by switching between the modes of operation at each time step, using a heating mode control signal.

Figure 11: Synthetic model of dual fuel heating



Constraints on technology efficiency levels imposed by codes and standards:

The efficiency of each system type is regulated by state and federal codes and standards that set minimum efficiency level requirements, including 10 CFR 430.32(c) and CA Appliance Efficiency Regulations – Title 20 Section 1605.1(c) and 1605.1(e).

The codes and standards that apply to gas furnaces and heat pumps, as well as air conditioners, are shown below in Tables 8-10. Table 8 indicates Minimum Seasonal Energy Efficiency Ratio 2 (SEER 2) and Heating Seasonal Performance Ratio 2 (HSPF2) for units manufactured on or after 1/1/23 [13]. Table 9 is Table E-6 of CA Appliance Efficiency Regulations in Section 1605.1(e)(1) Standards for Gas- and Oil-Fired Central Furnaces Less Than 225,000 Btu/hour Input and Residential Electric Furnaces [14]. Table 10 indicate standards for Non-Federally Regulated Central Furnaces (California Title 20, Table E-8) [13].

Standards for Non-Federally- Regulated Central Furnaces (California Title 20, Table E-8) which come from Measure Packages [13].

- SWHC049-03: SEER Rated AC and HP HVAC Equipment, Residential
- SWHC031-03: Furnace, Residential

Table 8: Minimum SEER 2 and HSPF2 for units manufactured on or after 1/1/23 [13]

PRODUCT CLASS	MINIMUM EFFICIENCY EFFECTIVE JANUARY 1, 2023			
	MINIMUM SEER2	MINIMUM HSPF2	MINIMUM EER2***	AVERAGE OFF-MODE POWER CONSUMPTION $P_{W,PFF}$ (WATTS)
Split systems - air conditioners with a certified cooling capacity less than 45,000 Btu/hr	14.3	-	11.7/9.8†	30
Split systems - air conditioners with a certified cooling capacity equal to or greater than 45,000 Btu/hr	13.8	-	11.2/9.8††	30
Split system - heat pumps	14.3	7.5	-	33
Single-package units - air conditioners	13.4	-	10.6	30
Single-package units - heat pumps	13.4	6.7	-	33

Table 9: CA Appliance Efficiency Regulations-Standards for Central Furnaces [14]

Product class	AFUE (percent)	Maximum Electrical Power Consumption	
		Standby	Off Mode
(A) Non-weatherized gas furnaces (not including mobile home furnaces)	80	No requirement	
(B) Mobile Home gas furnaces	80	No requirement	
(C) Non-weatherized oil-fired furnaces (not including mobile home furnaces)	83	11	11
(D) Mobile Home oil-fired furnaces	75	11	11
(E) Weatherized gas furnaces	81	No requirement	
(F) Weatherized oil-fired furnaces	78	No requirement	
(G) Electrical furnaces	78	10	10

Table 10: Standards for Non-Federally Regulated Central Furnaces [13]

APPLIANCE	APPLICATION	MINIMUM EFFICIENCY %
Central furnaces with 3-phase electrical supply < 225,000 Btu/hour	Mobile Home	75 AFUE
	All others	78 AFUE or 80 Thermal Efficiency (at manufacturer's option)

Anticipated regulatory changes:

EPA is currently proposing a new ENERGY STAR furnace revision with an AFUE requirement of 97% for gas furnaces which aligns with current federal tax requirements. The effective date of implementation is yet unknown. The DOE had proposed changing the minimum efficiency requirement for furnaces to 90% AFUE, which is feasible with condensing furnace technology [15]. Although the rule faced legal hurdles, it is reasonable to expect that regulators will revisit the issue and attempt to increase the minimum efficiency requirement. If such a change were to take effect, it could become increasingly likely to find efficient furnaces in existing homes. Each incremental change to the assumption regarding furnace efficiency can shift the optimal control decision (whether to heat using furnace or heat pump) for the dual fuel heating system for several hours per year. So, the impacts of an increased furnace efficiency assumption would be overall lower annual emissions or operating costs (depending on the control optimization objective), and a lower number of hours that the heat pump would be selected.

Note that starting in 2023, code requirements for air conditioners and heat pumps are expressed in terms of SEER2, HSPF2, and EER2, which replace earlier ratings system of SEER, HSPF, and EER. The DEER models were developed using reference data in terms of SEER, HSPF, and EER. Note that 14.3 SEER2 is equivalent to 15 SEER, which is considered to be the code minimum efficiency for a typical residential, central, split system air conditioner or heat pump.

Background on DEER prototype models:

For deemed energy efficiency programs in California, a commonly used source of building energy models has been the DEER (Database of Energy Efficiency Resources) models that are calibrated with California-specific data. The latest set of DEER models for single-family residential buildings (SFm) use the Modelkit template system and EnergyPlus energy modeling engine. Among the DEER models is a single-family home prototype, which comes in many permutations accounting for:

- Measure Group (set of related DEER measures)
- Location (California climate zone or CZ)
- Cohort which is a combination of the following characteristics:
  - Building Type (SFxm)
  - Number of stories (1-story and 2-story)
  - HVAC Type (residential direct heat exchange air conditioning with gas furnace [rDXGF] and residential direct heat exchange air heat pump [rDXHP][2])
  - Vintage (median existing and new)
  - Tech Group (the type of technology that is the focus of the measure)
- Tech ID (the specific measure efficiency level and associated key parameter inputs)

Vintages:

The DEER residential models come in two varieties of building age, existing and new. The existing building model is intended to evaluate retrofits of existing homes and is designed to reflect the typical design choices for homes of the median existing vintage as a function of climate zone. The DEER memo on prototype development shows that the median existing vintage used to represent typical existing homes in DEER varies by climate zone (1975 for CZ 1-9 and 1985 for CZ 10-16) [16]. See Table 11 for details.

[2] DX is used to contrast with no-cooling or hydronic systems. dxAC in model names is synonymous with DXGF.

Table 11: Selected Vintage for Single-Family by Climate Zone [16]

Based on the vintage distribution for each climate zone, the most representative vintage per climate zone was chosen and is listed in Table 2-1 below. For example, for climate zone three (CZ3), over 75% of residential homes were built before 1978, so vintage 1975 was selected to represent the single-family residence stock.

Table 2-1 Selected vintage for each climate zone of single-family

CZ	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Vintage	1975	1975	1975	1975	1975	1975	1975	1975	1975	1985	1985	1985	1985	1985	1985	1985

Number of stories:

The DEER residential prototype generates separate models for single-story and two-story single-family homes. In practice, the results from both single and two-story models are used in measure packages by using a weighted average between the two models. The weighted average value depends on the vintage and climate zone. See Table 12 below for the weighted average values for each climate zone. The weighted average is rounded up or down to the nearest whole (single or two-story) to determine the cohort selected for each climate zone.

Table 12: Weighted Average Number of Stories by CZ

Climate Zone	Weighted Average Number of Stories	Rounded Number of Stories (to select cohort)
CZ01	1.48	1
CZ02	1.48	1
CZ03	1.48	1
CZ04	1.48	1
CZ05	1.48	1
CZ06	1.55	2
CZ07	1.55	2
CZ08	1.55	2
CZ09	1.33	1
CZ10	1.42	1
CZ11	1.23	1
CZ12	1.23	1
CZ13	1.23	1
CZ14	1.12	1
CZ15	1.12	1
CZ16	1.31	1

Efficiency Level:

The last determination that must be made is the efficiency level of the gas furnace and the heat pump. The models were compared using the baseline efficiencies, but this may not be appropriate for the final analysis scenarios since the investor-owned-utilities (IOUs) cannot incentivize code baseline equipment.

Heat pump efficiency:

One major highlight of the literature review findings is that when heat pumps are sized for the winter heating load, they often have too much capacity for the summer cooling loads. Multi-speed or variable speed compressors are therefore preferred when selecting a heat pump in a cold climate so the heat pump can perform optimally during the summer. The minimum heating seasonal performance factor (HSPF) that has a variable speed compressor is HSPF 9.0 which is paired with SEER 16. Therefore, this efficiency level is selected for the heat pump model.

Gas furnace efficiency:

CEDARS data was used to determine the most common efficiency level installed in California EE programs [17]. The most common gas furnace efficiency is 95% with a variable speed motor.

Final Model Selections:

The final model selections for the heat pump and the gas furnace are as follows:

- Vintage: 1975 for Climate Zones 01-09, 1985 for Climate Zones 10-16
- Stories: Dependent upon Climate Zone
- Heat Pump (HSPF 9/SEER 16)
  - Measure Group: SFm_SEER Rated AC_HP_1975/85
  - Tech ID: HSPF_9p0_SEER_16_Msr
- Gas Furnace (Gas furnace efficiency 95% AFUE)
  - Measure Group; SFm_Furnace_1975/85
  - Tech ID: Msr-Res-GasFurnace-AFUE95-ECM

Table 13 shows the typical properties of the building energy model instances, assumptions and data sources used in the analysis. For each California climate zone (16), hourly model outputs were generated for a heat pump and a gas furnace model.

Table 13: Properties of building energy model (BEM)

Model Assumption	Value
Building energy model	DEER EnergyPlus Single Family
Vintage	Median existing (circa 1975/1985 building energy code)
Size	Small (1-story / 1,400 ft^2)
Gas furnace efficiency	95% AFUE
Heat pump efficiency	7.7 HSPF2 / 9.0 HSPF
Heating capacity	Auto sized with 1.8 sizing factor
End-use load disaggregation	Heating and heating mode fan
Simulation time step	10 minutes
Cost and emissions calculation granularity	Hourly
Location/climate region	CEC Climate Zones 1-16, focus on CZ11 and CZ16
Weather data	CZ 2022 ten-year (typical meteorological year)
Emissions source	California Avoided Cost Calculator (ACC 2022)

6.2 Climate Zones and Rate Tariffs

The energy savings and simple payback to the end user is dependent upon the prices and rate structures of electricity and natural gas. Hence, an analysis was conducted using the available rate tariffs. As a function of climate zone, a model was assumed to have electric and gas utility service from the predominant provider for the climate zone. Within a limited scope of analysis used by deemed measure packages, CPUC *Resolution E-5009* determined the representative utility for each climate zone. Table 14 enlists the representative utility for each climate zone [19].

Table 14: Predominant PA to Use for Statewide Savings Analysis [19]

CA Climate Zone	Electric*	Gas*	IOU balancing area region**
CZ01	PG&E	PG&E	NP-15
CZ02	PG&E	PG&E	NP-15
CZ03	PG&E	PG&E	NP-15
CZ04	PG&E	PG&E	NP-15
CZ05	PG&E	PG&E	NP-15
CZ06	SCE	SCG	SP-15
CZ07	SDG&E	SDG&E	SP-15
CZ08	SCE	SCG	SP-15
CZ09	SCE	SCG	SP-15
CZ10	SCE	SCG	SP-15
CZ11	PG&E	PG&E	NP-15
CZ12	PG&E	PG&E	NP-15
CZ13	PG&E	PG&E	NP-15
CZ14	SCE	SCG	SP-15
CZ15	SCE	SCG	SP-15
CZ16	SCE	SCG	SP-15

* (California Public Utilities Commission, 2019)
** (Energy+Environmental Economics, 2022)

Electric rate tariffs and cost analysis:

Note that the IOUs offer a variety of electric rates applicable to single-family residential services. Customer bill savings and simple payback may vary depending on the customer rate tariff's energy and demand charges. Active rates were surveyed to observe key rate tariff features, drawing on rate tariffs and related documents published by PG&E, SCE, and SDG&E, and on the U.S. Utility Rate Database [19]. If the efficiency measure is implemented without concurrent change of customer rate tariff, then fixed service charges (such as daily or monthly service fees) are not relevant for payback calculations, so the rate tariff review focused energy and demand charges.

Table 15 summarizes the various tariffs by utility. It should be noted that some rate tariffs carry eligibility requirements based on income.

Table 15: Active Electric Rate Tariffs and Key Features

IOU	Tariff Option	Type	Qualifier	Details
PG&E	E-1	Tiered		Residential Services
	EM	Tiered		Master-Metered Multifamily Service
	ES	Tiered		Multifamily Service
	ESR	Tiered		Residential RV Park and Residential Marina Service
	ET	Tiered		Mobilehome Park Service
	EM-TOU	TOU		Residential Time-of-Use Service; multifamily/RV
	E-TOU-C	Tiered/TOU		Residential Time-of-Use Service
	E-TOU-D	TOU		Residential Time-of-Use Peak Pricing 5-8pm non-holiday weekdays
	EV	TOU	EV	Residential Time-of-Use Service for Plug-In Electric Vehicle Customers; EV separately metered
	EV2	TOU	EV	Residential Time-of-Use Service for Plug-In Electric Vehicle Customers; home and EV metered together
	E-ELEC	TOU	EV, Electric Home	Residential Time-of-Use (Electric Home) Service for Customers with Qualifying Electric Technologies
SCE	D	Tiered		Domestic Service
	D-CARE	Tiered	CARE program	California Alternate Rates for Energy Domestic Service
	DE	Tiered	SCE Employees	Domestic Service to Utility Employees
	D-FERA	Tiered	FERA Household	Family Electric Rate Assistance
	DM	Tiered		Multifamily Accommodation – Residential Hotel – Qualifying RV Park
	DMS-1	Tiered		Domestic Service Multifamily Accommodation – Submetered
	DMS-2	Tiered		Domestic Service Mobilehome Park Multifamily Accommodation – Submetered
	DMS-3	Tiered		Domestic Service Qualifying RV Park Accommodation – Submetered

IOU	Tariff Option	Type	Qualifier	Details
	D-SDP	–	Direct load control device	Domestic Summer Discount Plan
	ESC-OO	–	No smart meter	Edison SmartConnect Opt-out
	MB-E	–	Medical baseline allocation	Medical Baseline – Exemption
	SEP	–	Direct load control device	Smart Energy Program
	TOU-D-4-9PM	TOU		Time-of-Use Domestic (peak, off-peak, super off-peak)
	TOU-D-5-8PM	TOU		Time-of-Use Domestic (peak, off-peak, super off-peak)
	TOU-D-PRIME	TOU	EV or Battery or HPWH or HP HVAC	Time-of-Use Domestic (peak, off-peak, super off-peak)
SDG&E	DR	Tiered		Domestic Service
	TOU-DR	TOU		Residential – Time of Use Service
	DR-SES	TOU	Solar energy system	Domestic Time-of-Use for Households with a Solar Energy System
	E-CARE	–	CARE program	California Alternate Rates for Energy Program
	DM	Tiered		Multi-Family Service
	DT-RV	Tiered		Submetered Service – Recreational Vehicle Parks and Residential Marinas
	EV-TOU	TOU	EV	Domestic Time-of-Use for Electric Vehicle Charging
	EV-TOU-2	TOU	EV	Domestic Time-of-Use for Households with Electric Vehicles
	EV-TOU-5	TOU	EV	Cost-Based Domestic Time-of-Use for Households with Electric Vehicles
	DE	–	SDGE Employees	Domestic Service to Utility Employees

IOU	Tariff Option	Type	Qualifier	Details
	FERA	–	FERA Household	Family Electric Rate Assistance Program
	E-SMOP	–	No smart meter	Electric Residential Smart Meter Opt-Out Program
	TOU-DR1	Tiered/TOU		Residential Time-of-Use
	TOU-DR2	TOU		Residential Time-of-Use
	DAC-GT	–	DAC-GT Program	Disadvantaged Communities Green Tariff (DAC-GT)
	CSGT	–	CSGT Program	Community Solar Green Tariff
	TOU-ELEC	TOU	EV or Battery or HPWH or HP HVAC	Domestic Time-of-Use for Households with Electric Vehicles, Energy Storage, or Heat Pumps

For the current work, in order to mitigate the issue of sensitivity to the usage of the single, representative building model for select applications (involving only the heating system load, and/or incremental changes in usage, and/or requiring an hourly price signal), simplified rate calculations were prepared as listed in Table 16.

For example, in the simplified spreadsheet analysis of heating systems comparing baseline and measure case equipment, where only one end-use load is modeled and the remaining building loads are omitted, the simplified rate calculation for marginal hourly costs may be used in place of the full rate tariff.

Table 16: Rate calculation types and relevance

Rate calculation type	Relevance
Full rate tariff	Whole-building energy models
Representative marginal hourly cost ($/kWh)	Price signals for optimization Incremental usage changes Comparison (base case and measure case)
Average hourly cost ($/kWh)	Breakdown of building systems energy costs

Gas rate tariffs and cost analysis

The simple payback to the end user is also dependent upon the price of natural gas, so an analysis was done on rate tariffs for natural gas. A representative set of costs per therm of natural gas for single-family homes was determined using several data sources as noted in Table 17. The default residential gas tariffs for 3 IOUs are highlighted.

Table 17: Active Gas Rate Tariffs and Key Features

IOU	Tariff Option	Type	Qualifier	Details
PG&E	**G-1**	**Tiered**		**Residential Service**
	GM	Tiered		Master-Metered Multifamily Service
	GS	Tiered		Multifamily Service
	G1-NGV	-	NGV/HRA	Residential Natural Gas Service for Compression on Customers' Premises
	GL-1	Tiered	CARE Program	Residential CARE Program Service
	GML	Tiered	CARE Program	Master-Metered Multifamily CARE Program Service
	GSL	Tiered	CARE Program	Multifamily CARE Program Service
	GTL	Tiered	CARE Program	Mobilehome Park CARE Program Service
	GL1-NGV	-	CARE Program	Residential CARE Program Natural Gas Service for Compression on Customers' Premises
SoCalGas	**GR**	**Tiered**		**Residential Service**
	G-NGVR	-	NGV/HRA	Natural Gas Service for Home Refueling of Motor Vehicles
	G-CARE	-	CARE Program	California Alternate Rate for Energy (CARE) Program
	GO-AC	Tiered	Gas AC	Optional Rate - Air Conditioning
SDG&E	**GR**	**Tiered**		**Domestic Natural Gas Service**
	G-CARE	-	CARE Program	California Alternate Rate for Energy (CARE) Program
	G-NGVR	-	NGV/HRA	Natural Gas Service for Home Refueling of Motor Vehicles
	G-SMOP	-	Analog Meter	Residential Gas Smart Meter Opt-Out Program

See Table 18 for average electric and gas rates by climate zone and rate tariffs used for the analysis.

Note that the average rates in Table 18 were used for climate zone screening and marginal hourly rates were used for analysis of control algorithms and pareto front.

Table 18: Average electric and natural gas rates by Climate Zone

Climate zone	Name of electric utility	Name of gas utility	Average Rate [$/kWh]	Average Rate [$/therm]
01	PG&E	PG&E	$0.405	$1.678
02	PG&E	PG&E	$0.395	$1.696
03	PG&E	PG&E	$0.410	$1.678
04	PG&E	PG&E	$0.396	$1.701
05	PG&E	PG&E	$0.410	$1.683
06	SCE	SoCalGas	$0.338	$1.539
07	SDG&E	SDG&E	$0.488	$2.207
08	SCE	SoCalGas	$0.341	$1.542
09	SCE	SoCalGas	$0.331	$1.532
10	SCE	SoCalGas	$0.325	$1.548
11	PG&E	PG&E	$0.387	$1.750
12	PG&E	PG&E	$0.389	$1.738
13	PG&E	PG&E	$0.390	$1.757
14	SCE	SoCalGas	$0.336	$1.523
15	SCE	SoCalGas	$0.317	$1.554
16	SCE	SoCalGas	$0.331	$1.539

Note: While the methods presented here are a best effort for evaluating typical customer utility bill changes and payback, it should be noted that utility rates are subject to change due to volatile fuel prices and regulatory and/or legislative initiatives. See Appendix A2 for more details on proposed legislative driven electric rate changes to adopt a fixed price based on household income in California and later changes to add a new minimum monthly charge.

6.3 GHG Emissions Factors

Building energy models output site energy usage (electric kWh and gas therms), so to evaluate and optimize source fuel usage or greenhouse gas emissions (GHG emissions), source fuel factors and GHG factors were selected from available data sources. Several data sources for source fuel factors and GHG emissions factors are available including the NREL Cambium database, US EPA eGRID database, California Energy Commission (CEC) time dependent valuation of energy (TDV) and source energy factors, and the CPUC California Avoided Cost Calculator (ACC) [20].

The ACC is used for evaluating cost-effectiveness of CPUC-regulated energy efficiency and demand response programs [20]. The ACC source-site energy factors are made available as a lookup table that varies by utility, hour of the year, and year. The year-on-year changes reflect projections regarding the annual grid load, new generation, and fraction of renewable generation in the grid following the state's renewable portfolio standards (RPS) requirements. As for emissions, the ACC includes an assumption that can be used to derive emissions from source energy.

It should be noted that ACC factors are typical values considering typical weather and grid load patterns over several years. Also, the ACC factors evaluate marginal operating source energy and emissions, rather than averages since the key application for these factors is for evaluating the benefits of incremental changes from efficiency and demand response measures. Because of its relevance to regulated incentive programs and its derivation from typical data rather than a single year of historical data, the 2022 ACC was selected as the source most representative source of both source fuel and emissions factors. For the current work, the source fuel, and emissions factors from the 2022 ACC were captured in a workbook, as lookup tables that vary by location/utility, hour of the year, and year.

Hourly electric emissions data came from ACC Electric Model, which gives hourly emissions for all Investor-Owned Utilities (IOUs) for the years 2022-2052. 2022 emissions were used for the analysis. The emissions for each IOU were averaged for each hour to get an average hourly emission dataset for 8,760 hours. An example of the individual hourly emissions by IOU and the average emissions used in the analysis are shown for January 1, 2022, in Appendix A3.

The source fuel factor for natural gas was a constant value also obtained from the 2022 ACC.

7.0 Analysis

7.1 Total HVAC Electricity Costs and Total Gas Furnace Heating Costs

The following sections will detail the analysis to determine the annual HVAC fuel costs and HVAC emissions for each climate zone. In summary, hourly models were generated for a heat pump and a natural gas furnace model for sixteen (16) climate zones. Then, average natural gas and electric fuel costs and hourly emissions for natural gas and electricity were gathered. The data was put into a spreadsheet analysis to calculate the HVAC fuel costs and HVAC emissions for each hour for the natural gas furnace and a heat pump. See Equation 1 and Equation 2 for calculating HVAC fuel costs.

Equation 1

$$GasFurnaceFuelCost = SupplyFanElec_{Gas-Furnace} * ElecRate_{CZ} + HVACNatGas * GasRate_{CZ}$$

Equation 2

$$HeatPumpFuelCost = \left(HeatingOnlyElec_{HeatPump}\right) * ElecRate_{CZ}$$

Where:

$GasFurnaceFuelCost$ *is the total HVAC fuel cost for the gas furnace system.*

$HeatPumpFuelCost$ *is the total HVAC fuel cost for the heat pump system.*

$SupplyFanElec_{Gas-Furnace}$ *is the electric use of the supply fan in heating mode for the gas furnace system.*

$HeatingOnlyElec_{HeatPump}$ *is the electric use of the Supply Fan, electric resistance, and Heating Compressor for the heat pump system.*

$ElecRate_{CZ}$ *is the average electricity price by climate zone (from Appendix A1).*

$GasRate_{CZ}$ *Is the average natural gas price by climate zone (from **Error! Reference source not found.** A1).*

An algorithm was created to choose which system had the lowest fuel cost or the lowest emissions for each hour. In order to select the system that would cost least to operate between natural gas furnace and heat pump, control logic from Figure 12 was applied. In order to determine the system that would have the least amount of emissions between the natural gas furnace and heat pump, control logic from Figure 13 was applied. Then, the results were summed over all hours of the year to determine the annual total fuel costs and emissions for HVAC system.

Figure 12: Control Logic to select preferred system to minimize fuel cost

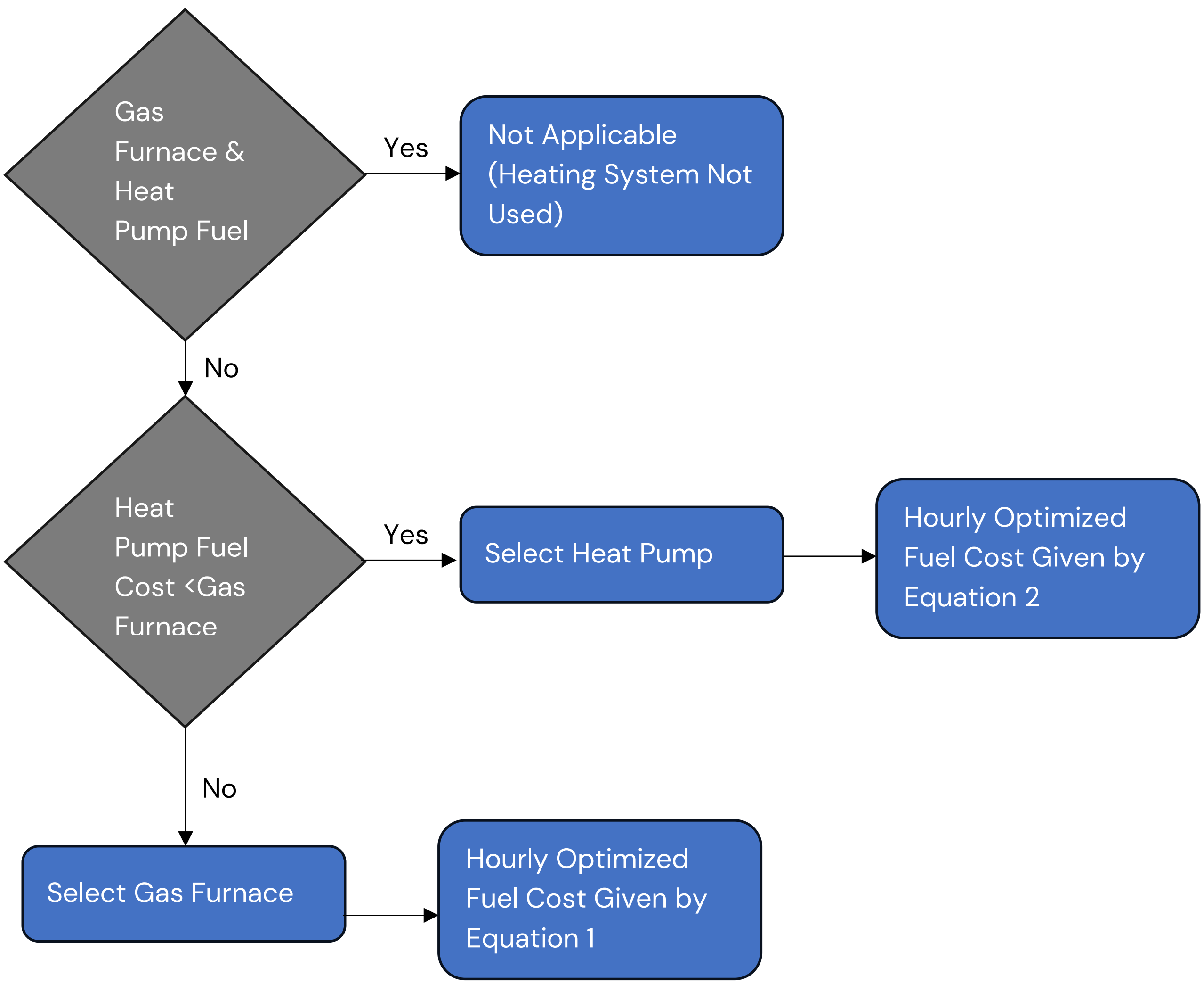


Figure 13: Control Logic to select preferred system to minimize emissions.

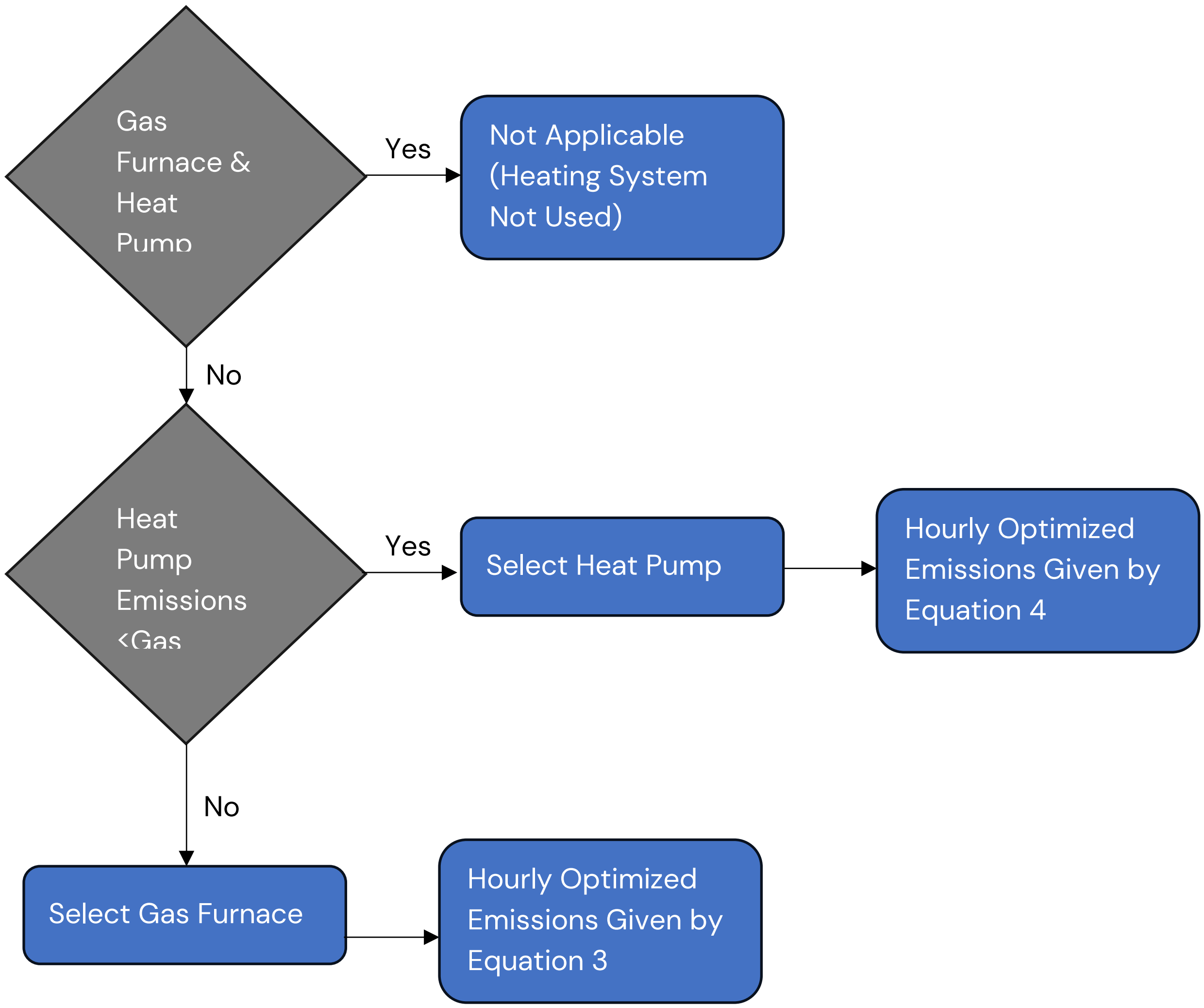


Table 19 shows the annual HVAC fuel costs and emissions data for all sixteen (16) climate zones. Two (2) climate zones were selected for future tasks and comprehensive analysis. The final selected climate zones are Climate Zone 11 and Climate Zone 16. See Table 20 for results for selected climate zones. These climate zones were selected because they exhibit significant savings potential for both reducing emissions (relative to a gas furnace baseline) and reducing fuel costs (relative to a heat pump baseline). Due to the disparity in the natural gas and electric rates in California, there is no scenario where the dual fuel heating system saves fuel cost when compared to a gas furnace only system (note that average rate was used in the calculation). Additionally, due to the hourly emissions shapes in California, there are very few hours of the year where a dual fuel heating system would save emissions compared to an electric heat pump only system.

Table 19: Annual HVAC fuel costs and emissions data for climate zone screening

Climate Zone	Annual HVAC Fuel Cost[3] [$]				Annual HVAC Emissions [tonnes CO2]		
	Gas Furnace	Heat Pump	Preferred System for Minimum Cost	Preferred System for Minimum Emissions	Gas Furnace	Heat Pump	Preferred System for Minimum Emissions
1	$166.28	$446.25	$166.26	$405.20	0.497	0.414	0.408
2	$317.68	$728.43	$317.67	$709.34	0.918	0.708	0.705
3	$249.01	$543.89	$249.01	$540.91	0.701	0.509	0.509
4	$222.76	$485.60	$222.76	$482.07	0.631	0.470	0.470
5	$263.16	$587.02	$263.16	$584.98	0.745	0.547	0.546
6	$145.37	$268.53	$145.37	$268.01	0.434	0.310	0.310
7	$214.19	$360.88	$214.19	$360.64	0.425	0.287	0.287
8	$147.95	$250.76	$147.87	$249.64	0.427	0.287	0.286
9	$163.66	$294.76	$163.66	$294.43	0.493	0.348	0.348
10	$89.24	$205.47	$89.24	$186.16	0.281	0.248	0.244
11	$222.63	$518.13	$222.62	$462.14	0.620	0.523	0.514
12	$221.58	$521.02	$221.57	$475.46	0.620	0.527	0.519
13	$229.93	$501.86	$229.93	$480.80	0.627	0.510	0.506
14	$233.61	$458.06	$233.57	$441.93	0.698	0.541	0.539
15	$73.07	$134.03	$73.04	$126.23	0.219	0.165	0.162
16	$124.83	$282.56	$124.81	$247.45	0.393	0.336	0.319

[3] HVAC system fuel costs here were calculated using average cost per unit energy method.

Table 20: Annual Estimated Emissions and Cost Savings- CZ 11 and CZ 16

	Climate Zone 11	Climate Zone 16
HVAC Fuel Cost: Gas Furnace	$222.63	$124.83
HVAC Fuel Cost: Heat Pump	$518.13	$282.56
Fuel Cost Using Preferred System for Cost[4]	$222.62	$124.81
Annual Fuel costs Using Preferred System for Emissions[5]	$462.14	$247.45
Fuel Cost savings: Dual Fuel (when minimizing emissions) vs. Heat Pump	$55.99	$35.11
Fuel Cost Savings (% of Heat Pump Fuel Cost)	11%	12%
Fuel Cost Increase: Dual Fuel (when minimizing emissions) vs. Gas Furnace	$239.52	$122.63
Fuel Cost increase (% of Gas Furnace Fuel Cost)	108%	98%
Annual HVAC Emissions: Gas Furnace [Metric Tonnes CO_2]	0.62	0.39
Annual HVAC Emissions: Heat Pump [Metric Tonnes CO_2]	0.52	0.34
Annual HVAC Emissions Using Preferred System for Emissions[6]	0.51	0.32
Emissions Savings: Dual Fuel vs. Heat Pump	0.01	0.02
Emission Savings (% of Heat Pump Emissions)	2%	5%

7.2 Pareto Front Optimal Analysis

One of the original expected outcomes from this project was to optimize the switchover temperature for minimized annual fuel costs and usage and for minimized GHG emissions. However, the results from the initial cost and emissions analyses in the previous section showed that using our modeling assumptions and under the current utility tariffs and California grid emissions:

1. There were an insignificantly small number of hours where heat pump mode was preferred over furnace mode subject to a requirement for minimum operating cost.
2. Subject to a requirement for minimum emissions, there were an insignificant number of hours that furnace was preferred.

It is common in exploratory research that questions evolve as the research progresses. In fact, the findings and interpretation will often suggest what questions are at the heart of the

[4] Preferred system to minimize **fuel cost** calculated on an hourly basis.
[5] Preferred system to minimize **source emissions** calculated on an hourly basis.
[6] See Note 2.

subject. Analysis of initial questions yields preliminary findings, preliminary findings support or oppose initial hypotheses, and researchers gain insight that allows them to rewrite or refine the questions. The findings above lead to a revision in scope for the rest of this study to explore sensitivity to fuel costs and control strategy.

In the analysis that follows, operating costs for HVAC were calculated using a marginal fuel cost per unit energy rather than an average fuel cost. As shown in Table 16, this method is well suited to evaluating changes in operating cost due to small incremental changes in usage. Varying the controls within a given home should yield such incremental changes. The marginal fuel costs were determined by applying the full rate tariff to the whole building usage profile for the gas furnace home as a baseline.

7.2.1 Scenario focus area 1 - Cost ratio

The first finding suggests that rather than fix the analysis to the current utility rates, which would not address the issue, the ratio of electric-to-gas operating costs for energy should be treated as a variable that will evolve. Given the uncertainty in the energy market, it is reasonable to consider a range of values for the ratio between operating fuel costs as potential outcomes. The previously written optimization scenarios could be rephrased with the **ratio of electric-to-gas operating costs now being considered a variable in a parametric study**:

- Visualize Seasonal/hourly data with nondimensional variables such as (a) ratio of heat pump energy use rate to furnace energy use rate and (b) ratio of electric-to-gas operating costs for energy. Repeat plot with color code by category variable such as outdoor temperature and TOU period.
- Plot key optimization results (total annual operating cost, energy and emissions, savings, and fraction of heating hours or loads delivered in heat pump mode) vs operating electric-to-gas operating cost ratio.
- Identify break-even points of electric-to-gas operating cost ratio (zero-crossing points on plots) where the optimal control solution (minimizing annual operating cost) yields emissions reductions of 5%, 25%, 50%, and 75% of the difference between solo furnace and solo heat pump operation. Repeat analysis with filter/aggregation by (a) time of day and (b) Seasonal/TOU period.
- Investigate key variables that determine operating cost decision and develop visualization to illustrate the tradeoff: outdoor temperature, electric-to-gas operating cost ratio, system efficiency ratios, time of day, and Seasonal/TOU period (including hypothetical periods such as winter morning).

7.2.2 Scenario focus area 2 – Emissions vs Cost

The second finding suggests that the tradeoff between emissions and operating cost should be investigated, in particular by considering the effect of introducing a cost credit per unit emissions savings ($ / tonne CO2e) as an additional parametric variable. Introducing an operating cost credit would be a linear transformation to the optimization problem, which could result in changes to the presence of an optimal point or break-even points to minimize emissions.

For background, in optimization problems dealing with tradeoffs between multiple objectives, a common methodology is to plot a curve called the "Pareto optimal front." The curve consists of all the points that are optimal under some objective function that is a linear combination of the multiple objectives (annual emissions and operating), and it also represents a boundary on the set of feasible outcomes in the objective space (no control function will outperform the points on the curve). The features revealed by viewing the Pareto optimal front are the inflection and departure of the curve between its endpoints, and the relative alignment of specific modes of operation viewed as key data points. For example, 100% furnace operation typically aligns near one end of the curve with low cost and high emissions, and 100% heat pump operation typically aligns near another end of the curve with high cost and low emissions. The inflection and departure of the curve from a straight line between those endpoints indicates whether there may be an optimum for an objective function that is a linear combination of emissions and operating cost. Visualizations of the Pareto optimal front provide researchers with a visual aid to quickly interpret the tradeoffs between emissions and operating cost, for example, the rate of incremental emissions savings per incremental operating cost increase.

Here are the key observations that could be made from a focus on a **parametric study with respect to emissions reduction cost credit and visualizing the Pareto optimal front:**

- Plot of Pareto optimal front for emissions vs operating cost optimization problem, without emissions reduction credit.
- Plot of transformed Pareto optimal front for emissions vs operating cost optimization problem, with emissions reduction credit at various levels.
- Results of optimization plotted against emissions reduction credit.
- Identify emissions reduction credit values that would yield an optimal control solution (minimizing annual operating cost) that exhibits emissions reductions of 5%, 25%, 50%, and 75% of the difference between solo furnace and solo heat pump operation.

7.2.3 Scenario focus area 3 – Emissions datasets

Underlying any emissions optimization analysis are the emissions factors. Multiple sets of historical grid emissions figures are available from different sources: for example, CAISO and WattTime. As discussed previously, multiple sets of grid emissions forecast figures are available from different sources: for example, CPUC ACC and NREL Cambium database. The ACC data set was used during initial analysis, but during the initial review of the data, the consistency and impact of these data sets was raised.

In this focus area, two datasets were compared (CPUC ACC and Watt Time historical emissions data for year 2022 with grid region CAISO North). The implications of choosing one dataset over another for this class of dual fuel analysis problems was also discussed. To clarify, this third focus area would exclude repeating analyses from focus areas 1 and 2. Instead, this focus area intended to deliver a *limited effort*, direct comparison between two emissions factors datasets considered. It did not include normalizing datasets to other factors such as hourly grid load, outside air temperature, etc.

7.2.4 Pareto Front Results

To fully understand the potential for reducing annual emissions and operating costs when operating a dual-fuel heating system, the trade-off between these two objectives was first examined by charting the Pareto front. The Pareto front represents the boundary of possible solutions for annual emissions and operating costs, considering all possible control signal sequences. (For this analysis, allowable controls were constrained to selecting between gas furnace operating mode and heat pump operating mode for each hour of the year). This information is important because it allows the customer to make an informed decision about how to operate the dual fuel system, and it allows further analysis of how changes in rate tariffs or other economic incentives could impact annual outcomes.

Figure 14 shows the Pareto front for the CZ 16 single-family model with ACC 2022 emissions data and flat rate electric tariff. Notable points are overlaid, clockwise from bottom: solo gas furnace (P_0), minimum annual cost (P_c), minimum emissions (P_e), and solo heat pump (P_1). In between the minimum cost and minimum emissions points, each point on the Pareto front indicates an annual operating profile that minimizes operating cost for a given level of emissions, or vice versa. Figure 14 shows the potential outcomes from static switchover temperature controls, varying by switchover temperature setpoint, overlaid on the Pareto front. As the setpoint increases, the controls approach solo gas furnace operation; as the setpoint decreases, the controls approach solo heat pump operation. Note that at 50% relative emissions reduction (about 0.355 metric tonnes/year), the annual operating cost for the Pareto optimal point is substantially lower than that for the switchover temperature controls. Furthermore, the switchover temperature controls may achieve results near the minimum emissions point, but do not achieve 100% feasible emissions reductions. Seeing the potential for reducing operating costs, a later section discusses the design and performance of controls that are informed by the cost and emissions minimization results. Note that in terms of percentage savings, there is less potential for the controls to create variation in emissions (18%) than there is in potential to cause variation in costs (50%) under this scenario.

Figures 15-17 illustrate the results with other CZs and tariff options.

Figure 14: Pareto optimal front, CZ 16, flat rate electric tariff.

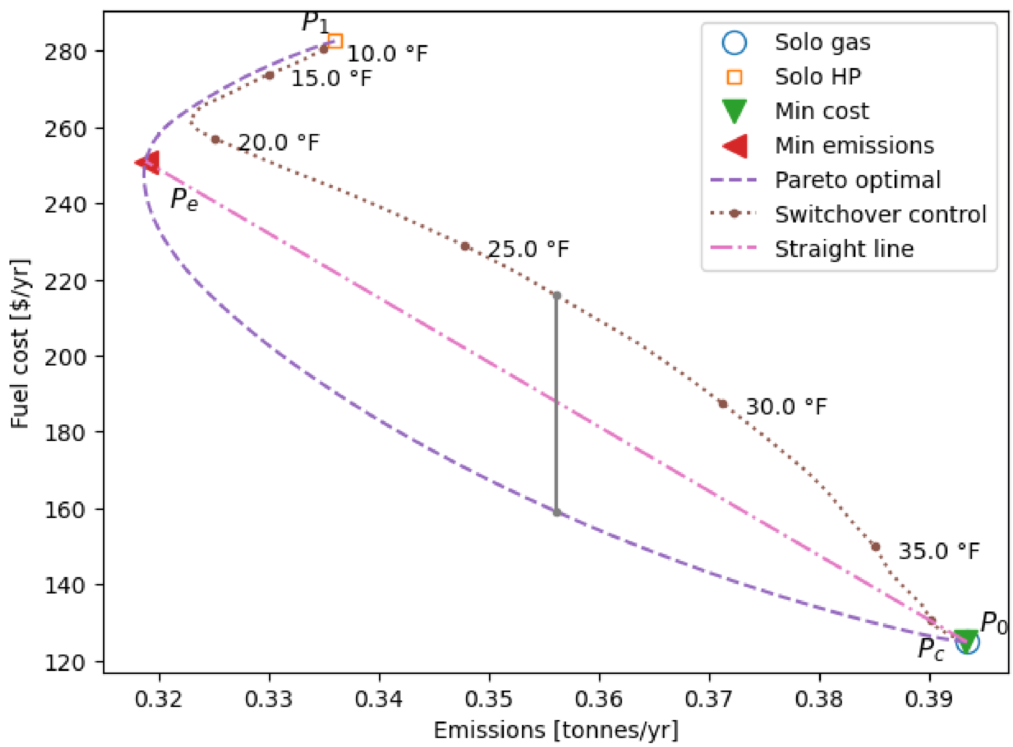


Figure 15: Pareto optimal front, CZ 16, TOU electric tariff.

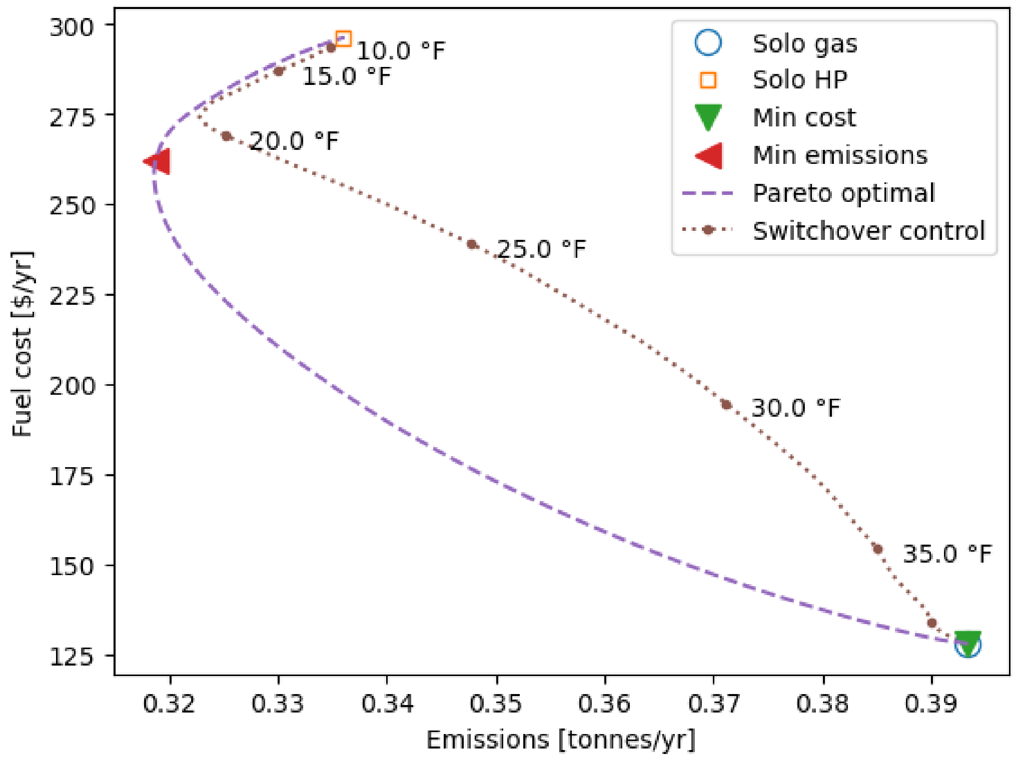


Figure 16: Pareto optimal front, CZ 11, flat rate electric tariff.

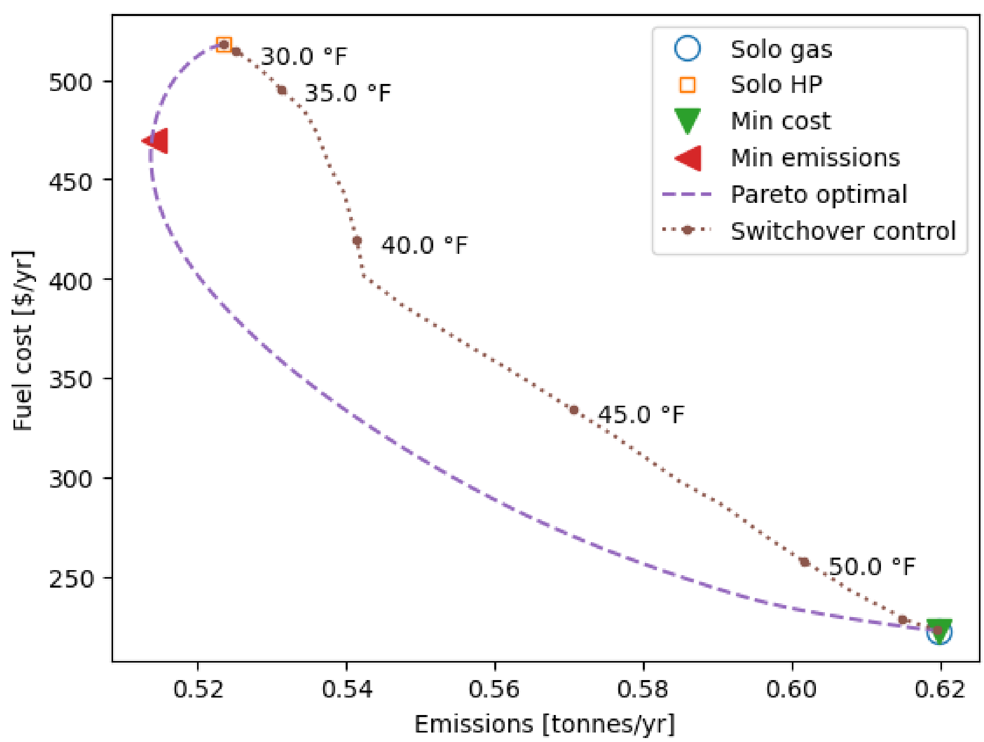
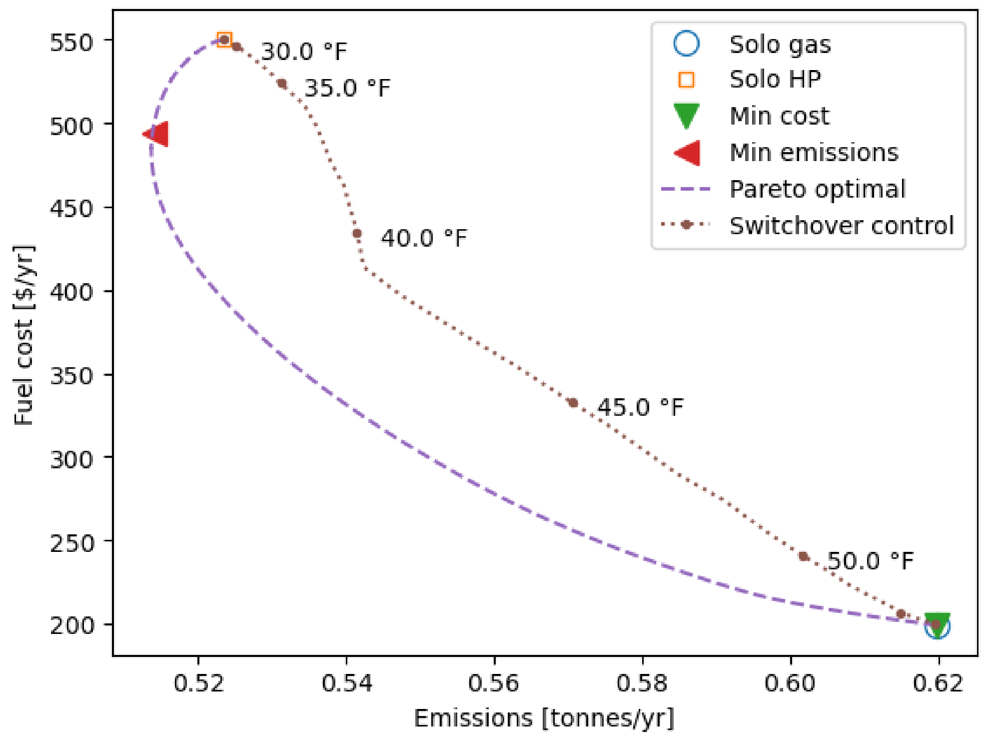


Figure 17: Pareto optimal front, CZ 11, TOU electric tariff.



7.3 Analysis of Heating Load Shape and Emissions Factor Profile

The scenario to minimize emissions is sensitive to both the hourly emissions factor of the electric grid as well as the heating load of the home. These two factors combined determine whether the lowest emissions option is the furnace or the heat pump. In this section there are some visual representations of the home heating load shapes in CZ 11 and CZ 16 compared to the ACC winter emissions factor profile to show why the heat pump is almost always preferred for emissions reduction.

The furnace natural gas usage from the EnergyPlus models output data was used to determine the heating load shape. The furnace natural gas use for each hour in each season was averaged to determine the seasonal heating load profile. Similarly, the emissions factor using the ACC data for each hour in each season was calculated to show the seasonal emissions profile. Figure 18 and Figure 19 show the ACC emissions profile and winter heating load shape for each CZ (11 and 16, respectively). The yellow box on the chart highlights the peak heating load in each CZ. As expected, peak heating loads occur in the morning. CZ 11 shows a secondary heating peak in the nighttime while CZ 16 doesn't have a secondary peak, but its heating load steadily increases starting around 9 PM.

Note that at the same time each CZ experiences its peak heating load, the emissions in both climate zones are at their secondary peak rather than their primary peak. This is the reason that even at the peak heating loads, the heat pump operation is usually preferred to minimize emissions for single family heating applications.

However, this data also points to potential future electric grid constraints and changes to the forecasted emissions profile in the winter morning hours as more homes in California electrify. It also shows potential for a strategy to pre-heat a home in the early hours of the morning to reduce this heating load peak much like precooling a building in the early afternoon reduces the late afternoon/early evening cooling load peak. However, unlike precooling, which is done before peak temperatures (in the summer), preheating could increase overall heating energy consumption.

See Appendix A4 for more details on comparison of GHG emissions datasets.

Figure 18: CZ 11 Emissions Factor Profile and Heating Load Shape

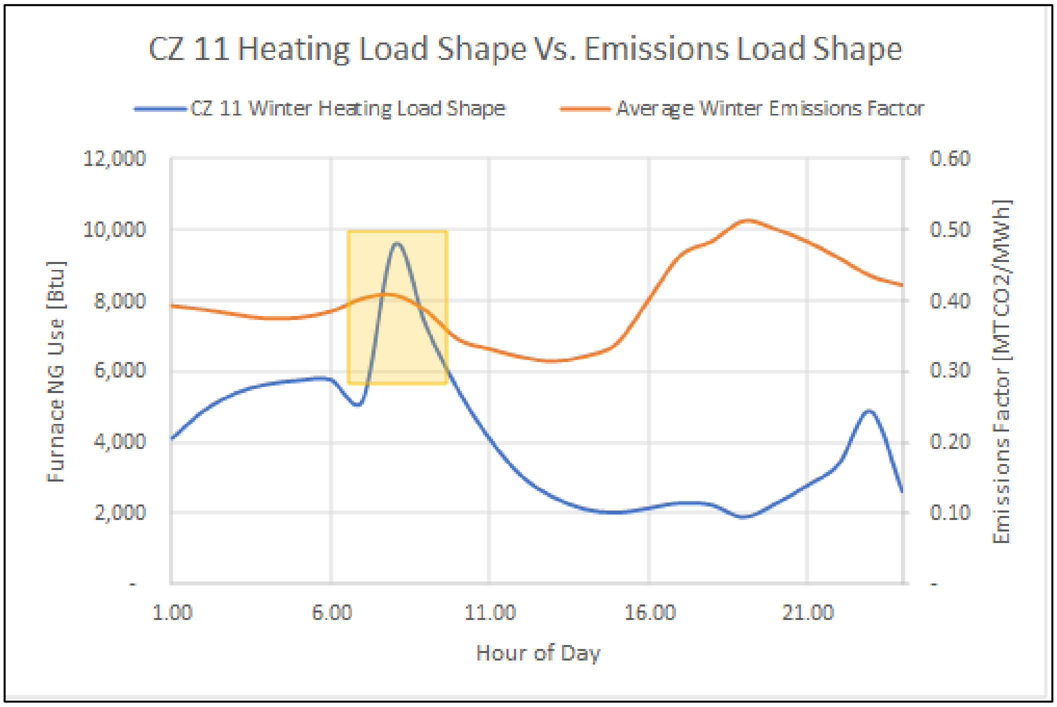
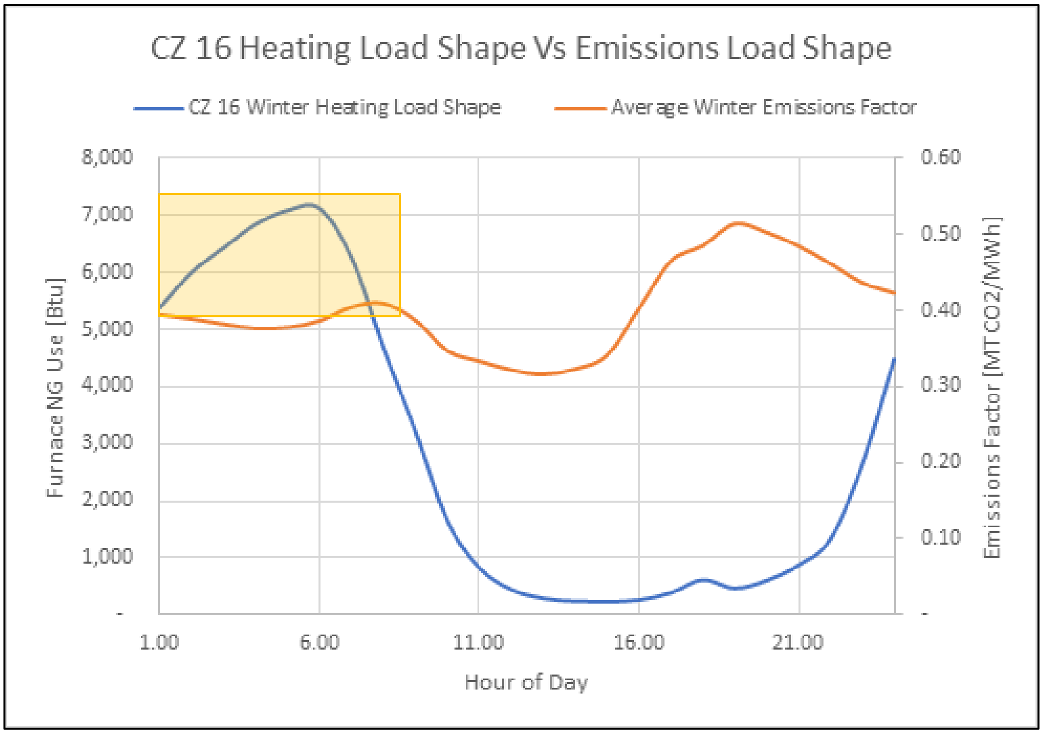


Figure 19: CZ 16 Emissions Factor Profile and Heating Load Shape



7.4 Parametric Analyses

7.4.1 Parametric variation of fuel costs

While the previous section assumed the present marginal rate structures for electric and gas utilities, this section treats the rates as a parametric variable and considers the impact on the results as the costs are varied. There are several reasons for considering costs different from the present rate structures. For instance, rates are subject to change, and electric and gas costs may escalate at a different pace over time. Also, considering rates as a variable allows utilities to consider how rates can influence customer choices, or to observe the combinations of fuel costs at which a given technology will be economical for the customer. In particular, the ratio between electric and gas rates influences the relative costs of operating a dual fuel system in heat pump or gas furnace mode. By varying the costs for electric energy, this analysis is indirectly varying the ratio between electric and gas costs.

Figure 20 shows how the Pareto front evolves as the electric operating costs are scaled by a multiplier relative to current electric rates, uniformly across all hours of the year. Note that the cost scaling can be described by the Equation 3:

Equation 3

Electric costs (scaled rates) at time t [$/hr] = (Cost scalar) × Electric costs (current rates) at time t [$/hr]

Figure 20: Parametric variation of electric costs, CZ 16, flat rate electric tariff.

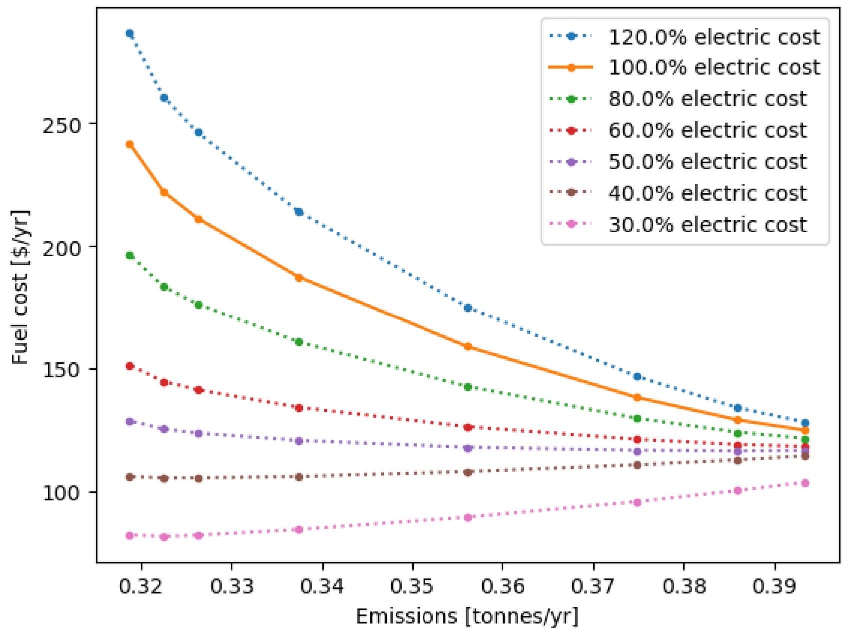
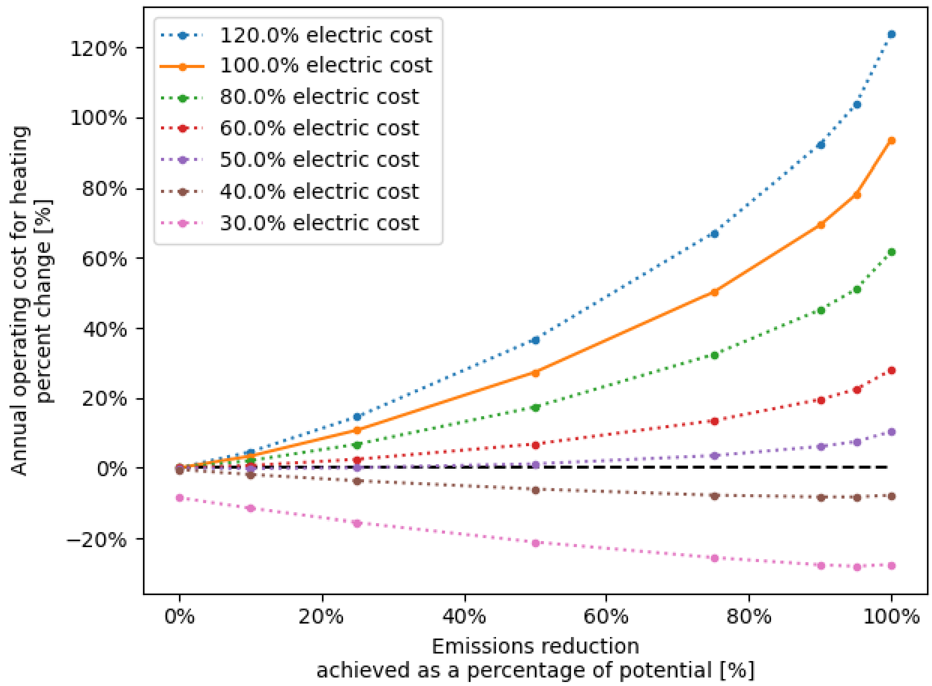


Figure 21 shows the same information translated into relative quantities with heating operating cost percent change plotted on the ordinate (y-axis) against emissions reduction divided by maximum emissions reduction potential on the abscissa (x-axis). Both quantities are calculated against solo gas furnace operation as a baseline.

Figure 21: Percent change - parametric variation of electric costs, CZ 16, flat rate.



At present rates (100% of present electric costs, and 100% of current gas costs), the cost to operate the heating system in CZ 16 increases up to double as emissions are reduced (by increasing the number of hours heating with a heat pump vs the cheaper to run gas furnace). If electric costs are reduced relative to current gas costs, the annual operating cost flattens out. At 80% of present electric-to-gas cost ratio, there is a modest cost premium (~ 17%) to achieve 50% of emissions reduction potential. At 60% of present electric rate-to gas cost ratio, there is a smaller cost premium (~ 7%) to achieve 50% of emissions reduction potential. And at approximately 45% of the present electric-gas cost ratio, there is no cost premium to achieve 100% of emissions reduction potential. Figures 22 and 23 below show similar results for CZ 11.

Figure 22: Parametric variation of electric costs, CZ 11, flat rate electric tariff.

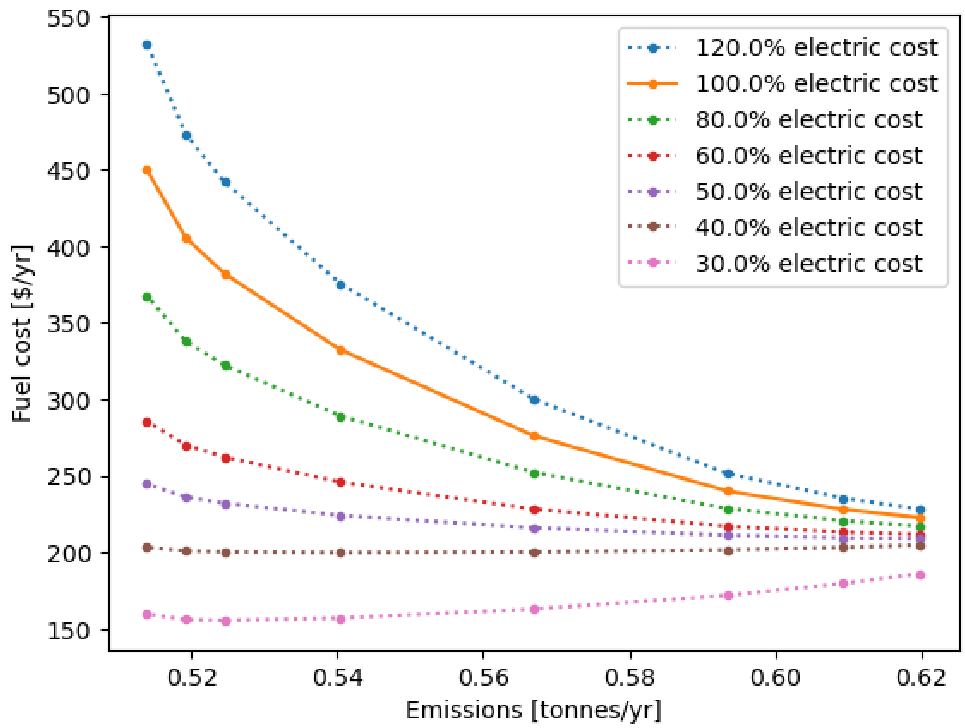
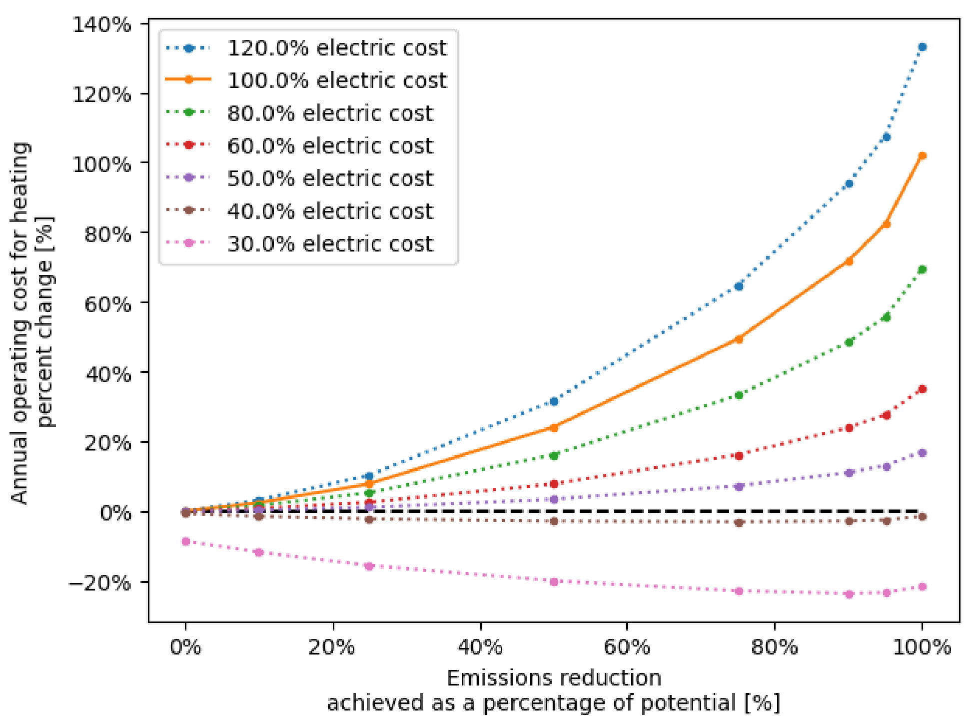


Figure 23: Percent change - parametric variation of electric costs, CZ 11, flat rate.

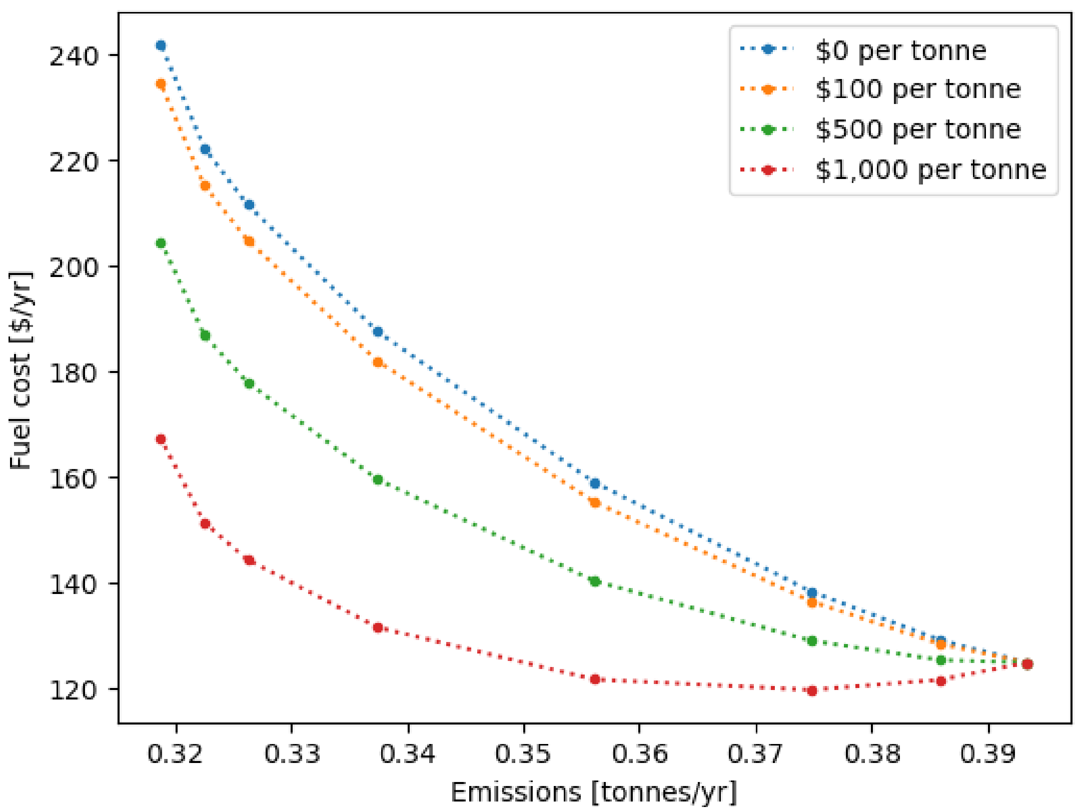


7.4.2 Parametric Variation of Emissions Cost or Credit

While the previous sections assumed customer operating costs are only priced based on unit fuel usage (electric $/kWh or gas $/therm), this section assumes that customer operating costs also include an emissions reduction component. The customer is granted a credit per unit emissions reduction ($/Metric tonne (MT) of CO2 reduced) relative to a gas furnace baseline. The amount of credit is varied to study the impact on the customer economics.

Figure 24 shows how the Pareto front evolves as the emissions cost credit varies.

Figure 24: Parametric variation of emissions credit, CZ 16, flat rate electric tariff.

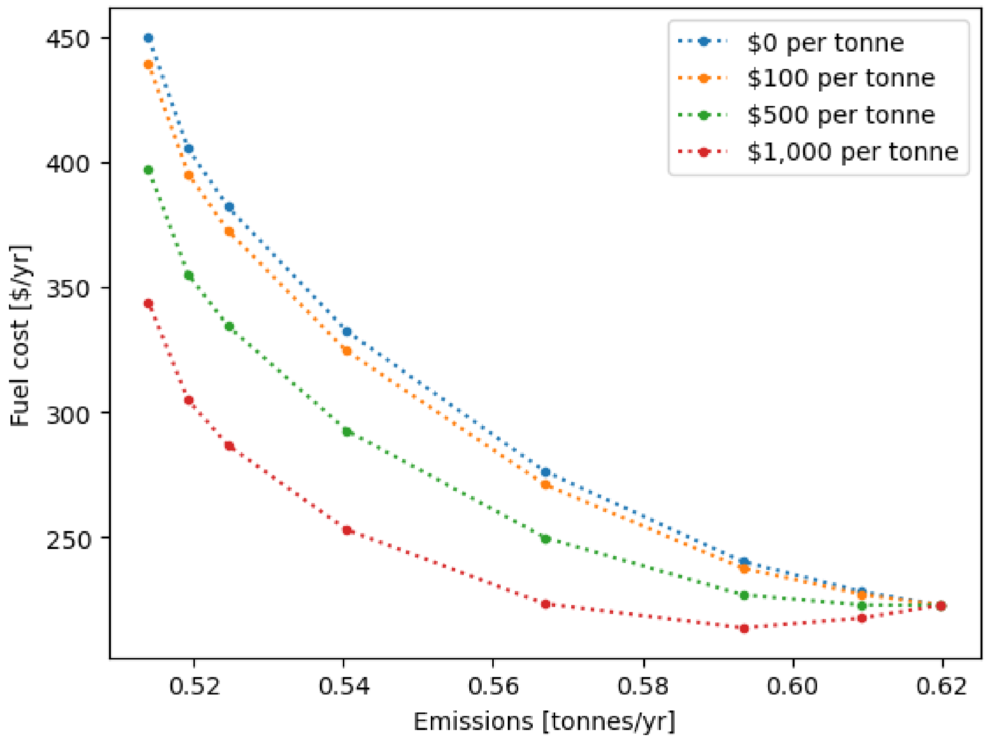


At a credit of $100/tonne, the customer faces a 24% operating cost premium to achieve 50% of emissions reduction potential compared to 27% without the credit. At a credit of $500/tonne, the operating cost premium for the same goal is only 12%. For comparison, within the California Cap and Trade program (which would not be applicable to this customer class), cap and trade credit is approximately $38.73/tonne as of Q4 2023 [23].

Note that this analysis does not specify any reason or contractual structure of the emissions-related cost component. Also note that from a technical perspective, the economics of the customer trade-off between operating costs and emissions are identical whether the emissions cost component is represented as a credit or not.

Figure 25 shows similar results for CZ 11.

Figure 25: Parametric variation of emissions credit, CZ 11, flat rate electric tariff.



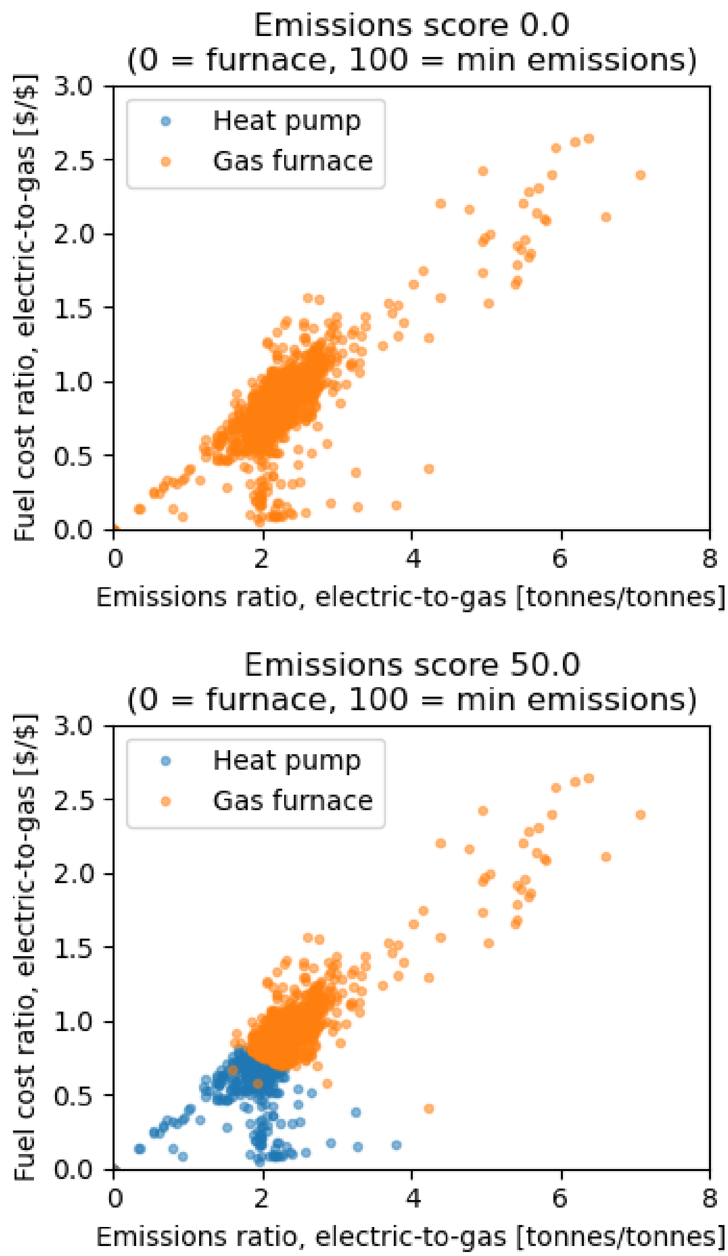
7.4.3 Pareto Front Analysis- Design of Controller

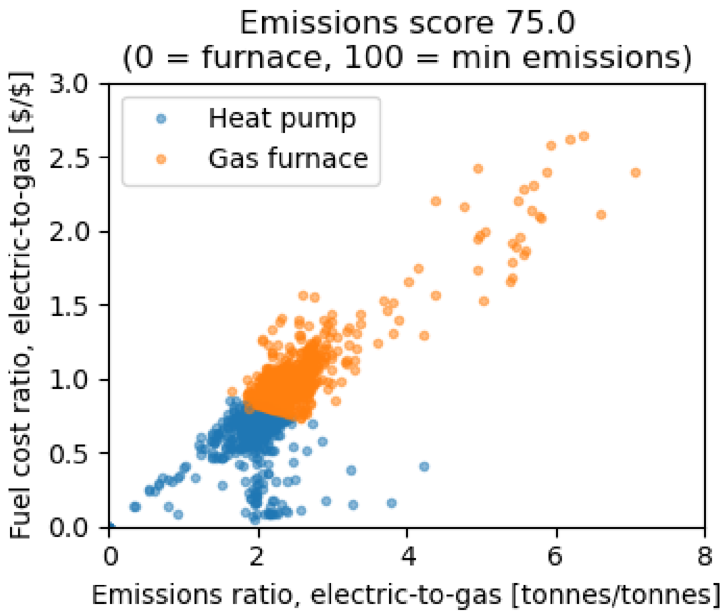
The analysis for drawing the Pareto front yields a set of control signal sequences that are optimized for emissions and cost, based on the input data for weather, emissions intensity, and operating costs. Suppose the customer prefers an outcome that achieves 50% of emissions reduction potential. A dual fuel mode controller should aim to produce signals that are similar to the optimization results for that point on the Pareto front. One possible approach to design the controller is to train it based on the optimization results.

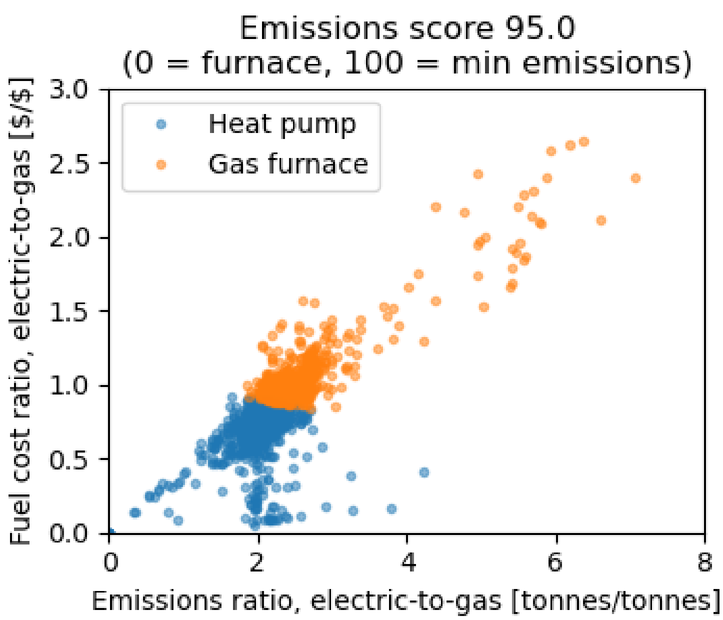
a) Training the controller

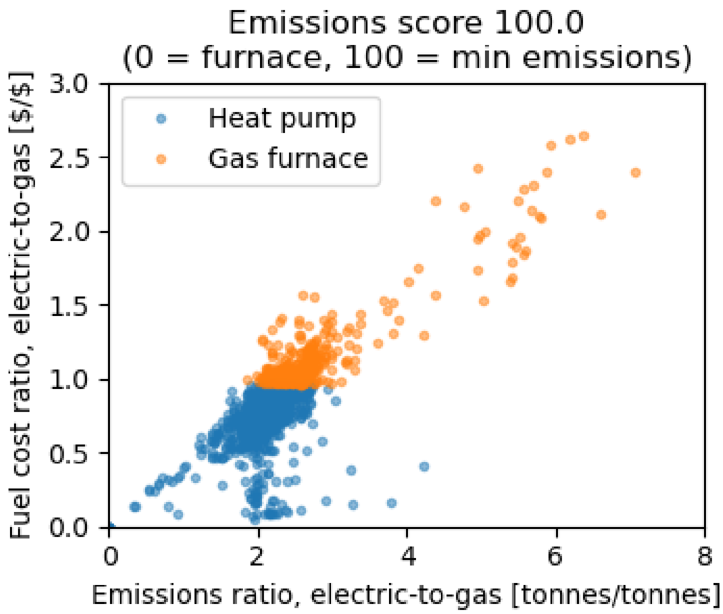
Figure 26 shows a scatterplot of costs and emissions for each operating interval in a one-year simulation. The color reflects the operating mode (gas furnace or heat pump) selected in each hour by the annual optimization routine. Visually, it appears that the optimal control output for a given hour can be classified based on the position in cost-emissions state space.

Figure 26: Electric-to-gas ratios, cost and emissions, CZ 16, flat rate electric tariff.




Emissions score 75.0
(0 = furnace, 100 = min emissions)
Heat pump
Gas furnace
Fuel cost ratio, electric-to-gas [$/$]
Emissions ratio, electric-to-gas [tonnes/tonnes]
0.0
0.5
1.0
1.5
2.0
2.5
3.0
0
2
4
6
8

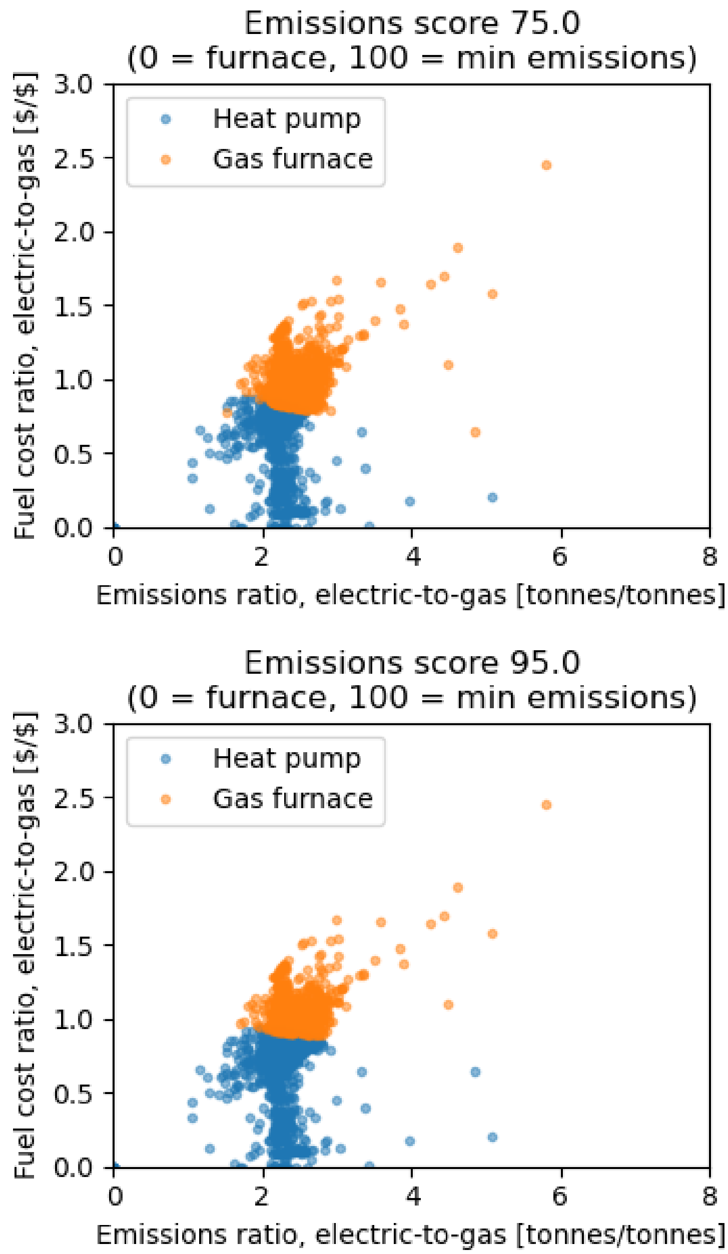

Emissions score 95.0
(0 = furnace, 100 = min emissions)
Heat pump
Gas furnace
Fuel cost ratio, electric-to-gas [$/$]
Emissions ratio, electric-to-gas [tonnes/tonnes]
0.0
0.5
1.0
1.5
2.0
2.5
3.0
0
2
4
6
8



With this control strategy, there may be year-to-year variations in the actual emissions reduction and cost. Future research could investigate the distribution of results for this control strategy given a setpoint for maximum $/tonne, by applying varying sources of weather data to the simulation and various years of emissions data to the analysis.

Figure 27 shows the results of the same analysis in CZ 11.

Figure 27: Electric-to-gas ratios, cost and emissions, CZ 11, flat rate electric tariff.

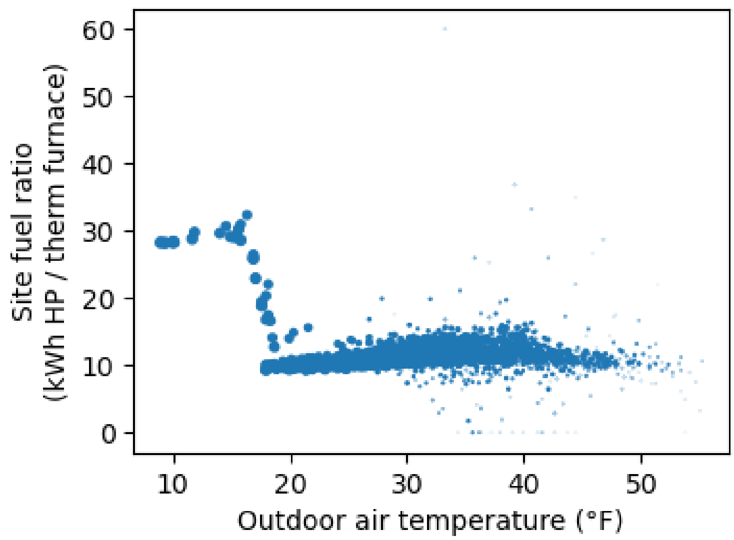


b) Weather-sensitive Heating Load and Equipment Performance

The present work assumes a "typical year" weather file for building energy simulations. Actual weather varies from year to year, with more heating demand and more energy usage associated with colder outdoor temperatures. With other factors being held constant, the relative fuel usage for heat pump and furnace modes is correlated with outdoor temperature. Note that this trend is highly sensitive to the individual heat pump model because the heat pump performance map (a function of indoor and outdoor temperatures and heating demand) depends on the equipment design.

Figure 28 shows the trend data for this relationship. In the denominator of the ratio, furnace energy usage includes furnace fan electric energy converted to thermal units. In this plot, the size of scatter points is proportional to furnace heating demand, meant to obscure hours points with little heating demand.

Figure 28: Relative fuel usage, HP, and furnace vs outdoor temperature, CZ 16.



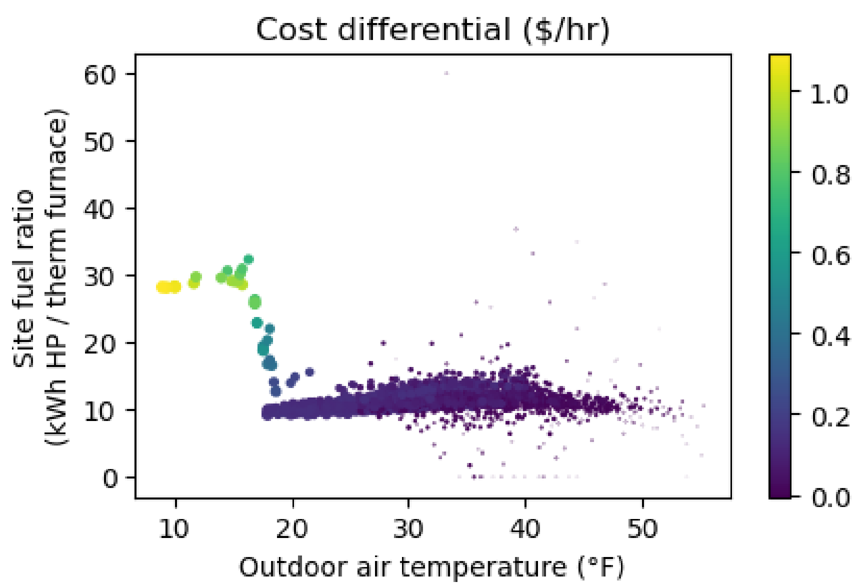
One way to interpret this correlation is that in a year with more hours of extreme cold (when heat pump is inoperable or has limited capacity), there may be less potential for emissions reduction during those hours. However, in a cold year, there may also be more hours of mild cold, with greater potential for emissions reduction during those hours.

By comparing annual outcomes for controls with fixed switchover temperature setpoint to the annual outcomes on the Pareto front, it is evident that an input signal for outdoor air temperature on its own is not enough information for a controller to achieve optimal performance in terms of costs and emissions. Hence, there is no value in deriving a relationship between temperature and the optimal operating mode for a dual fuel heating system in cases where the natural gas/electric cost ratio is low, and the climate is mild. Rather, future analysis should continue to treat weather and outdoor temperature as a background assumption or input to energy models.

For added detail and quantification of uncertainty, future research in this area could include analysis of year-to-year variations in historical data or projections for outdoor temperature in individual climate zones.

Furthermore, Figure 29 shows that the cost differential between heat pump operation mode and furnace operation mode is nearly uniform across a broad range of outdoor air temperatures from 20 to 50 °F. However, where the ratio of relative fuel usage increases, there is a clear corresponding increase in the cost differential. In other words, the cost differential appears to be more sensitive to the ratio of relative fuel usage than it is sensitive to outdoor temperature.

Figure 29: Cost differential, HP vs furnace, CZ 16, flat rate electric tariff.



c) Hourly variations and key variables

This section offers an exploratory investigation of how the range and interaction of time-varying variables impact the outcomes for switching from a furnace to a dual fuel system, drawing on visualizations of simulation data from CZ 16. The potential for emissions reductions and the operating cost trade-off to achieve them is a function of these key variables, including:

- Nominal equipment efficiency,
- Weather-sensitive heating load and equipment performance,
- Unit energy prices that may vary by season and time of day, and
- Emissions factors for grid electricity (tonne CO_2e/kWh) that may vary in real time, along with relatively flat gas emissions factors (tonne CO_2e/therm).

The variation of individual time-varying variables can be described in quantitative terms by their probability distributions (visualized via histograms), average profile (based on a cross-section of data, for example by time of day), and autocorrelation. The interaction between the variables can also be described in mathematical terms as a joint probability distribution of time-varying factors, which in common practice is investigated via visualization of a scatter plot of trend data. The following paragraphs employ these visualizations to offer qualitative observations that arise from examination of the data.

d) Impacts due to nominal equipment efficiency

The present work assumes a 95% AFUE furnace as a baseline, and a 9.0 HSPF central heat pump add-on in the dual-fuel system. If the customer has a different furnace efficiency or opts for a different heat pump efficiency, results will vary. To examine how the outcomes are sensitive to nominal equipment efficiency, consider the following examples:

Example 1: Suppose a customer has an 80% AFUE furnace baseline and installs a heat pump as an add-on to the heating system, with all other factors held the same as before. This lower efficiency baseline uses approximately 19% more energy per unit heating delivered than the 95% AFUE furnace baseline assumed in the preceding analysis. As a result, the baseline emissions and operating costs for heating are about 20% greater, so there is more potential for emissions reduction, and lower incremental operating costs associated with achieving the same levels of emissions reduction, compared to the prior analysis.

Example 2. Suppose a customer installs a 10.5 HSPF heat pump (typically 8.9 HSPF2) as an add-on to the heating system. Although an accurate prediction of heat pump energy usage requires more details (performance maps and weather), we can estimate that this heat pump uses approximately 14% less energy per unit heating delivered compared to the prior analysis. As a result, there is more potential for emissions reduction, and lower operating costs associated with achieving the same levels of emissions reduction, compared to the prior analysis.

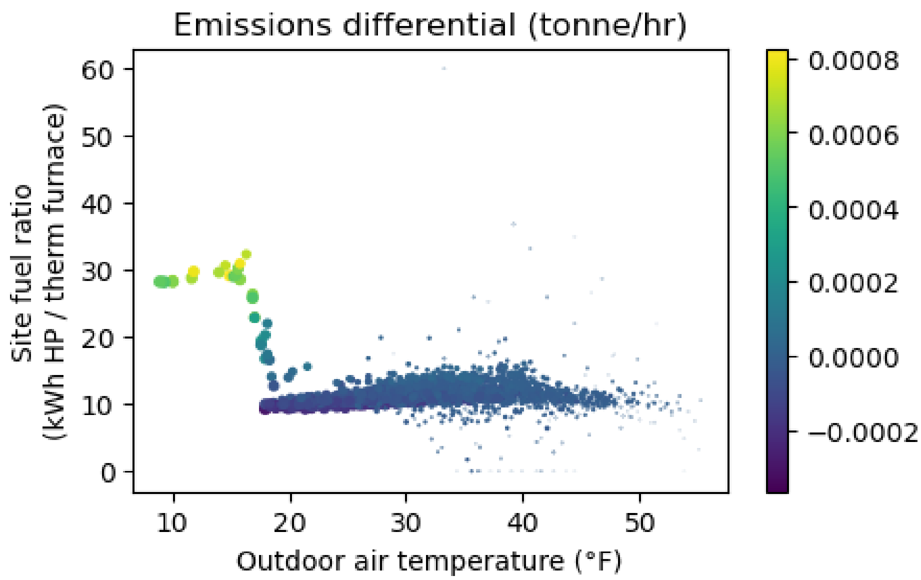
e) Emissions factors

For natural gas used to power a furnace, the gas emissions factor (representing fugitive emissions such as upstream distribution losses, measured in tonnes CO_2e/therm) is considered to be fairly insensitive to season and time of day, and it is not likely that a customer (or the customer controller) can obtain a site-specific figure, let alone real-time information.

For electricity used to power a heat pump and furnace fan, the electric emissions factor (tonnes CO_2e/kWh) in this analysis is taken to be the marginal emissions factor from the grid. There are several reasons that the electric emissions factor is significant. First, there is a large range of variation in the electric emissions factor due to variable renewable and non-renewable generation resources used. Second, the electric emissions factor is not predictable based on building sensors, such as temperature and time of day. There are commercially available real-time marginal emissions signals, as well as some information available from grid operators. Thus, it is technically feasible to design a controller to read in a signal representing the electric emissions factor. See Figure 30.

See Appendix A5 for more scatter plots on combined impacts for potential programming of the controller.

Figure 30: Emissions differential-heat pump and furnace operation modes- CZ 16



Following are the key remarks from the scatter plots:

- The analysis for drawing the Pareto front yields a set of control signal sequences that are optimized for emissions and cost, based on the input data for weather, emissions intensity, and operating costs. It is technically feasible to design a controller to read in a signal representing the electric emissions factor.
- There is no value in deriving a relationship between outdoor temperature and the optimal operating mode for a dual fuel heating system in cases where the natural gas/electric cost ratio is low, and the climate is mild.
- Several factors affect the optimization of control signal sequences and design of the controller apart from outdoor air temperature such as equipment efficiency, weather sensitive equipment load and heating load, emission factors, and unit energy prices.
- The distribution of GHG emissions change and operating cost changes are multi-modal, with multiple peaks. The resulting emissions change per unit cost increase is not a normal (Gaussian) distribution but is skewed with most hours having low emissions saving potential.

7.5 Cost Effectiveness Analysis

The Cost Effectiveness Tool (CET) is used to determine the Total System Benefit (TSB) and Total Resource Cost (TRC) ratio for dual fuel heating technology [23,24]. This section defines the assumptions for CET Analysis and summarizes the TRC and TSB values for four (4) Pareto front points of two (2) selected climate zones.

Dual fuel heating systems can be implemented in a variety of configurations. However, replacement of an existing air conditioner with an electric heat pump and a controller to work in sequence with an existing natural gas furnace is considered as a proposed measure for this CET analysis.

Total energy savings is one important factor for Energy Efficiency (EE) programs. The measure costs and measure life are important factors or inputs to the CET tool. TRC and TSB are outcomes from the analysis. In this task, the energy savings and other cost effectiveness parameters for selected climate zones (CZ 11 and CZ 16) are used to calculate TRC and TSB. Measure costs are estimated based on the available information from reference measure package SWHC045-03 (Heat pump HVAC, Residential, Fuel Substitution) and Subject Matter Expert (SME) interview findings [26].

Table 21 indicates common assumptions for cost effectiveness analysis.

Table 21: Assumptions for cost-effectiveness analysis

Base case operating mode	Solo gas furnace
CET Version	24.1
First Year	2024
Avoided Costs	2024
Market Effects (Spillover)	Y
Normalizing unit	Tons-cooling

Table 22 and Table 23 summarize the energy savings values for four (4) Pareto front points of two (2) selected climate zones. Note that the sign convention is positive for energy savings. Therms and kWh savings are calculated using a high efficiency solo gas furnace operation as a baseline. The unit therms and kWh savings are calculated by subtracting the corresponding household consumption values for a solo gas furnace and dividing by the unit size of 1.74 tons for CZ 11 and 1.49 tons for CZ 16.

Table 22: Energy Savings Values for Pareto Front Points (CZ 16)

Pareto front point	kWh consumption per household	Therms consumption per household	Unit kWh 1st baseline per Cap-tons	Unit Therms 1st baseline per Cap-tons
Solo gas furnace-baseline	49.82	70.39	n/a	n/a
Solo heat pump (HP)	853.66	0.00	-539.49	47.24
Minimum cost	49.85	70.38	-0.02	0.01
Minimum emissions	727.73	6.57	-454.97	42.84
Emissions score 50 (optimal point)	245.37	50.51	-131.24	13.34

Table 23: Energy Savings Values for Pareto Front Points (CZ 11)

Pareto front point	kWh consumption per household	Therms consumption per household	Unit kWh 1st baseline per Cap-tons	Unit Therms 1st baseline per Cap-tons
Solo gas furnace-baseline	70.92	111.53	n/a	n/a
Solo heat pump (HP)	1,338.84	0.00	-728.69	64.10
Minimum cost	70.92	111.53	0.00	0.00
Minimum emissions	1,143.90	15.52	-616.66	55.18
Emissions score 50 (optimal point)	309.49	89.42	-137.11	12.71

CET Calculations Assumptions

The inputs to the CET are determined using engineering judgement. Table 24 represents the CET inputs that are fixed for all the permutations. Table 25 represents the CET inputs that vary by the permutations.

Fixed CET inputs:

Net-to-Gross Ratio (NTG), Installation Rates, and Realization Rates: A NTG value of 0.85 was the input for all the emerging technologies. Installation Rates and Realization rates were set to 1.0 for all measures.

EUL: The Effective Useful Life (EUL) is selected to be 15 years for the dual fuel heating technology. This is consistent with the reference measure package - SWHC045-03 (Heat pump HVAC, Residential, Fuel Substitution).

Table 24: Fixed CET Inputs for All Permutations

CET Input	Value
Sector	Residential
DeliveryType	DnDeemed
BldgType	SFm
E3GasSavProfile	Annual
E3MeaElecEndUseShape	DEER:HVAC_Eff_HP
TechGroup	dxHP_equip
UseCategory	HVAC
UseSubCategory	HeatCool
NormUnit	Cap-Tons
NTG_ID	ET-Default
NTGRkWh	0.85
NTGRTherm	0.85
NTGRCost	0.85
EUL_ID	HV-ResHP
EUL_Yrs	15
RUL_ID	HV-ResHP
MeasImpactType	DEER
UnitRefrigBens	0
RealizationRatekWh	1
RealizationRateTherm	1

Varying CET inputs:

RUL: The Remaining Useful Life (RUL) is assumed to be 5 years for Accelerated Replacement (AR).

Refrigerant Costs and Benefits: The heat pump, like the air conditioner being replaced, contains refrigerant with a global warming potential (GWP) that can become a source of GHG emissions if leakage occurs. Leakage is not a normal part of operation, but in a large population of equipment leakage may occur due to component failures over time. The amount of leakage is expected to be proportional to the quantity of refrigerant contained within the equipment refrigerant charge. Research by California Air Resources Board (CARB) finds that a typical residential heat pump contains more refrigerant than a typical air conditioner of the same rated capacity and owners experience the same rate of leakage for both types of equipment, and therefore on average GHG emissions due to refrigerant leakage are slightly higher for heat pumps [25]. The current CPUC guidance for EE programs is to evaluate the detrimental impact of refrigerant leakage in terms of a cost component (UnitRefrigCosts) that counts against the TSB, using a Refrigerant Avoided Cost Calculator (RACC) workbook [25]. Therefore, this measure has UnitRefriCosts in the CET input table that are based on the CARB estimates for refrigerant charge and leakage rates. The value for this input is found using the Refrigerant Avoided Cost Calculator (RACC) version 2.2 assuming that R-410a is used. Note that refrigerant rules coming into effect in 2025 will reduce GWP of refrigerants in new HVAC equipment, and technologies and best practices are available that may contribute to reducing the leakage rates. Hence, unit refrigerant costs for are expected to fall over time, so the analysis considers the TRC and TSB outcomes with and without refrigerant leakage costs.

Table 25: Variable CET Inputs for Permutations

CET Input	Value
MeasAppType	NR or AR
E3ClimateZone	11 or 16
UnitMeaCost1stBaseline	$426 for NR and $2,194 for AR [27]
UnitMeaCost2ndBaseline	$0 for NR and $583 for AR [27]
MeasAppType	NR or AR
PA	SCE, SCG for CZ16 and PGE for CZ11
RUL_Yrs	0 for NR and 5 for AR [27]
UnitRefrigCosts	$[i]75 for NR and $172 for AR [27]

CET Outputs and Summary Tables:

TRC and TSB values are calculated with no incentive and with the incentive equal to 50% as well as 100% of the measure cost. Additionally, the impact of Measure Application Type (MAT) and climate zone on TRC and TSB values is studied.

Table 26 and Table 27 demonstrate the impact of incentive levels on the TRC and TSB values. TRC values are lower when an incentive equivalent to 50% and 100% of measure cost is considered. However, this decrease in TRC is insignificant. Note that there is no change in TSB values with a change in incentive levels.

Table 26: TRC Values – With and without incentives – CZ 11 and CZ 16

Pareto Front Point	TRC-CZ11 (Without Incentives)	TRC-CZ16 (Without Incentives)	TRC-CZ11 (With Incentive = 50% of measure cost)	TRC-CZ16 (With Incentive = 50% of measure cost)	TRC-CZ11 (With Incentive = measure cost)	TRC-CZ16 (With Incentive = measure cost)
Solo heat pump (HP)	1.07	0.84	1.04	0.81	1.01	0.79
Minimum cost	0.00	0.00	0.00	0.00	0.00	0.00
Minimum emissions	1.01	0.83	0.98	0.80	0.95	0.77
Emissions score 50 (optimal point)	0.40	0.39	0.37	0.37	0.35	0.35

Table 27: TSB Values - With and without incentives - CZ 11

Pareto Front Point	TSB-CZ11 (Without Incentives)	TSB-CZ16 (Without Incentives)	TSB-CZ11 (With Incentive = 50% of measure cost)	TSB-CZ16 (With Incentive = 50% of measure cost)	TSB-CZ11 (With Incentive = measure cost)	TSB-CZ16 (With Incentive = measure cost)
Solo heat pump (HP)	$461.50	$228.32	$461.50	$228.32	$461.50	$228.32
Minimum cost	-$67.49	-$67.32	-$67.49	-$67.32	-$67.49	-$67.32
Minimum emissions	$396.53	$232.66	$396.53	$232.66	$396.53	$232.66
Emissions score 50 (optimal point)	$43.37	$35.82	$43.37	$35.82	$43.37	$35.82

TRC and TSB values are compared for both the selected climate zones in Table 28. The average values are higher for CZ 11 if compared to CZ 16 for all the permutations. This difference can be attributed to the difference in operating hours of the gas furnace. On an average for all the pareto front points, the gas furnace runs longer in CZ 11 as compared to CZ 16. Note that this comparison is done for Normal Replacement measure type, Incentive level is 50% of the measure cost and the unit refrigeration costs are included.

Table 28: TRC and TSB Values - Climate Zone Comparison [7]

Climate Zone	Average TRC	Average TSB
CZ11	0.6	$208.48
CZ16	0.5	$107.37

It is understood that often emerging technologies have lower TRCs and TSBs when they are first released into programs since they do not have the benefit of economies of scale. TRCs for dual fuel heating technology in the single-family home with incentive equivalent to 50% of the measure cost are 0.6 and 0.5 for CZ 11 and CZ 16 respectively under the assumptions previously stated.

[7] For Normal Replacement, Incentive = 50% of measure cost, With Unit refrigerant costs

8.0 Conclusions

This emerging technology study investigates the energy and utility cost savings potential of dual fuel heating technology in California based upon modeled building prototypes. First, the study included interviews with SMEs to gain more insights into comfort characteristics, pre-qualification characteristics of dual fuel heating systems and control methodologies. The study used DEER prototype models of single-family residential homes in California to analyze different dual fuel heating scenarios. The hourly heating load and emission factor trends indicate potential future electric grid constraints and changes to the forecasted emissions profile in the winter morning hours as more homes in California electrify. The impact of rate ratios and hypothetical emission reduction credits on energy and emissions savings of dual fuel heating systems was analyzed. The Cost Effectiveness Tool (CET) was used to determine the TSB and TRC for dual fuel heating technology in selected climate zones of California.

Following are the key conclusions or project findings:

- In California, there is not an “economic balance point” wherein the operating cost of the gas furnace would equal the operating cost of the heat pump. In fact, the operating cost of a dual fuel system is between 69% - 144% more than a solo gas furnace system.
- Likewise, there is rarely an “emissions balance point” wherein the greenhouse gas (GHG) emissions from the gas furnace equals the GHG emissions of the heat pump. The emissions savings of a dual fuel system are between 0% - 5% of the emissions from a solo heat pump system.
- To minimize emissions, controls trend toward using only the heat pump.
- To minimize costs, controls trend toward using only the gas furnace.
- The SME interviews indicate major barriers in implementing dual fuel heating systems such as lack of sophisticated control methodology or innovative thermostats, lack of availability of skilled contractors, information, and supply chain barriers.
- The choice of ACC (projected marginal emissions data) vs. Watt-Time (actual marginal emission data) will not impact energy savings and emissions savings.
- Space heating peak occurs at emissions secondary peak, meaning electric heat pump is usually still preferred to minimize emissions even at the space heating peak. However, this indicates that grid may become constrained in morning hours as more homes electrify and satisfy their heating needs using electricity instead of gas.
- There is a significant difference in marginal electric and natural gas rates in California. The current electric gas ratio would need to be reduced by 55% to achieve 100% emissions reduction for CZ 11 with no increase in operating costs.

- To achieve a 50% emissions reduction, at a credit of $100/tonne, the customer faces a 24% operating cost premium, and at $500/tonne, the operating cost premium is 12%. For comparison, within the California Cap and Trade program (which would not be applicable to this customer class), cap and trade credit is approximately $38.73/tonne as of Q4 2023 [23].
- The pareto front analysis demonstrates that a controller that can read emissions and price signals will be most effective at reducing emissions and fuel costs if compared to a static switchover temperature.
- There is no value in deriving a relationship between outdoor temperature and the optimal operating mode for a dual fuel heating system in cases where the natural gas/electric cost ratio is low, and the climate is mild.
- Several factors affect the optimization of control signal sequences and design of the controller apart from outdoor air temperature such as equipment efficiency, weather sensitive equipment load and heating load, emission factors, and unit energy prices.
- CEDARS CET Tool is used to determine the TSB and TRC for dual fuel heating technology in selected climate zones of California. The average values of TRC and TSB of CZ 11 are higher than CZ 16. The average values of TRC are 0.6 and 0.5 for CZ 11 and CZ 16 respectively. Also, the average values of TSB are $208.48 and $107.37 for CZ 11 and CZ 16 respectively.
- Analysis should continue to treat weather and outdoor temperature as a background assumption or input to energy models. For added detail and quantification of uncertainty, future research in this area could include analysis of year-to-year variations in historical data or projections for outdoor temperature in individual climate zones.

9.0 References

[1] Combating High Fuel Prices with Hybrid Heating, Report by CLASP and RAP, July 2022.

[2] Justin Margolies and Art Thayer. Advancing Beneficial Electrification: The Role of Dual Fuel Home Heating Systems in Cold Climates. NRECA Business & Technology Surveillance. March 2020.

[3] https://www.eia.gov/consumption/residential/data/2020/.

[4] https://www.energy.ca.gov/sites/default/files/2021-08/CEC-200-2021-005-PO.pdf.

[5] Dual Fuel and Gas Heat Pump Market Research, Prepared by Lieberman Research Group for Northwest Energy Efficiency Alliance (NEEA), June 2023. https://neea.org/img/documents/Dual-Fuel-and-Gas-Heat-Pump-Research.pdf.

[6] William Liss and Patricia Rowley, Report by GTI Energy, Assessment of Natural Gas and Electric Decarbonization in State of Colorado Residential Sector, September 2020. DOI: 10.13140/RG.2.2.15685.99049.

[7] 2019 Dual Fuel Air-Source Heat Pump Monitoring Report, Report by Slipstream, December 2019. Prepared for Michigan Electric Cooperative Association Energy Optimization Program.

[8] Future of Home Heating, Report by MaRS Cleantech and Enbridge Gas Canada, April 2018.

[9] Dr. Farzin Rad et.al., Smart Control for Optimum Residential Fuel Switching between Natural Gas and Electricity.

[10] https://slipstreaminc.org/sites/default/files/documents/downloads/001064_ASHPInstalllationGuide_ADA%20web.pdf

[11] Zhenning Li et. al., Oak Ridge National Laboratory, Seamlessly Fuel Flexible Heat pump with Optimal Model-based Control Strategies to Reduce Peak Demand, Utility Cost and CO_2 Emission, 2022.

[12] https://home.costhelper.com/gas-heat-pump.html#extres1.

[13] Southern California Edison, "SEER Rated AC and HP HVAC Equipment, Residential version 03," California eTRM, 2023. [Online]. Available: https://www.caetrm.com/measure/SWHC049/03/.

[14] Energy Code Ace, "20 Appliance Efficiency Regulations - Reference Ace v12.5," 2023. [Online]. Available: https://energycodeace.com/site/custom/public/reference-ace-t20/index.html#!Documents/section16051federalandstatestandardsforfederallyregulatedapplian.htm.

[15] https://www.energystar.gov/furnace-version-5-pd

[16] DNVGL, "EnergyPlus "Migration to EnergyPlus Webinar - First of three webinars describing the EnergyPlus transition"," 2022. [Online]. Available: https://cedars.sound-data.com/deer-resources/tools/energy-plus/.

[17] Claims data in CEDARS for the measure SWHC031 Furnace Residential.

[18] California Energy Commission. (2020, 6 1). *TN233261_20200601T140200_2022 TDV Source Energy CH4 Leak 20yr 15RA.xlsx*. Retrieved from Docket Log 19-BSTD-03: 2022 Energy Code Pre-Rulemaking: https://efiling.energy.ca.gov/Lists/DocketLog.aspx?docketnumber=19-BSTD-03.

[19] National Renewable Energy Laboratory. (n.d.). *United States Utility Rate Database*. Retrieved from OpenEI: https://apps.openei.org/USURDB/

[20] California Public Utilities Commission. (2022, May 5). *Decision 22-05-002: Decision Adopting Changes to the Avoided Cost Calculator*. Retrieved from Rulemaking 14-10-003: https://docs.cpuc.ca.gov/PublishedDocs/Published/G000/M474/K624/474624547.PDF

[21] Appliance Standards Awareness Project, "Furnaces," [Online]. Available: https://appliance-standards.org/product/furnaces. [Accessed 1 August 2023].

[22] CPUC *Resolution E-5009* (California Public Utilities Commission, 2019, pp. A-7)

[23] Cap-and-Trade Program Data Dashboard | California Air Resources Board.

[24] CPUC. 2001. California Standard Practice Manual: Economic Analysis of Demand-Side Programs and Projects.

[25] CPUC. 2021. Total System Benefit Technical Guidance Version 1.1. August 16.

[26] California Air Resources Board (CARB). 2017. "Potential Impact of the Kigali Amendment on California HFC Emissions."

[27] Southern California Edison (SCE) and DNV. 2023. "Deemed_Measure_RACC_Workbook_v2.2.xlsx."

[28] Reference measure package SWHC045-03 (Heat Pump- HVAC, Residential, Fuel Substitution).

A. Appendix

A1: Interview Questionnaire

Discussion on switch over temperature/control methodology:

1. Can you share your thoughts/insights on factors affecting switchover temperature between natural gas and electric? How does this affect the performance of dual fuel heating systems?
2. How does the commercially available thermostat/control system switch over between natural gas and electric?
3. What are the potential additions to the functionalities of existing thermostat/control system?
4. Decision based on pricing signal: How is the current fuel price being calculated? Is it cost to the utility OR cost to the actual customer?
5. Can the smart controller/thermostat use a tiered rate structure? If yes, how does it record the total energy consumption of a home?
6. Can you provide insights on the pre-qualifications required for installing a dual fuel heating system OR replacement of existing split AC with an ASHP?
7. Can you share your insights about the system configuration changes and estimated costs associated with the same? (Thermostat installation, ductwork, HVAC sizing calculations and efficiency pairing of furnace and electric HP)
8. Estimated measure costs, energy savings and typical payback periods.
9. What are the potential barriers/challenges in installing dual fuel heating systems?
10. Can you share your thoughts/understanding about the resiliency of dual fuel heating systems? What if one system (gas/electric) fails?
11. Can you share your thoughts about emissions savings from dual fuel heating systems in the near term (5-10 years)?

Qualitative comparison between systems: comfort, IAQ and maintenance costs

12. Did you conduct any survey on customer satisfaction, comfort preferences, thermostat behavior?
13. Can you share your thoughts on qualitative comparison between dual fuel, all-electric and gas heating systems? Some of the pointers include customer comfort, IAQ, overall maintenance costs, noise of operation etc.

A2: Joint IOUs AB 205 Rate Proposals

KTLA reports, "Southern California Edison, Pacific Gas & Electric, and San Diego Gas & Electric submitted an electric rate proposal in response to a new state law (AB 205) passed in 2022 requiring the California Public Utilities Commission (CPUC) to adopt a fixed price – based on household income - to help fund electric delivery infrastructure such as poles, wires, meters and customer service" (Nextstar Media Group, Inc., 2023).

With Income Graduated Fixed Charges (IGFCs), "most of the Joint IOUs' residential schedules will receive the same, four-bracket fixed charges, with the low-income fixed charges set at the household Income Brackets shown in Table II-2."[8] According to SDGE, "This approach dramatically reduces the average electric rate – the per kilowatt hour. This portion of a customer's bill, which is mostly related to the electricity purchased from natural gas, wind and solar plants, will continue to vary based on electricity usage." (San Diego Gas & Electric Company, 2023)

Below describes the rate design in the proposal:[9]

- Fixed cost categories, which result in class average monthly fixed charges of:
  - PG&E: $53/month
  - SDG&E: $74/month, including approval of its new proposed rate component, the Electrification Incentive Adjustment (EIA)
  - SCE: $49/month;
- IGFCs on the following residential rate schedules:
  - PG&E rate schedules: E-1, E-TOU-C, E-TOU-D, EV2-A, E-ELEC
  - SDG&E rate schedules: DR, TOU-DR1, TOU-DR2, EV-TOU-2, DR-SES, EV-TOU-5, TOU-DR, and TOU-ELEC
  - SCE rate schedules: TOU-D 4-9, TOU-D 5-8, Schedule D
- Considerations for including higher IGFCs for certain residential rate schedules that currently have fixed charges:
  - PG&E's Schedule E-ELEC
  - SDG&E's Schedules EV-TOU-5 and TOU-ELEC;
  - SCE's Schedule TOU-D-PRIME

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[8] Joint Testimony of Southern California Edison Company, Pacific Gas and Electric Company, and San Diego Gas & Electric Company (the Joint IOUs) Describing Income-Graduated Fixed Charge Proposals. Joint IOUs' Exhibit 1. May 3, 2023. Submitted under CPUC Rulemaking 22-07-005. Available online: https://www.cpuc.ca.gov/-/media/cpuc-website/divisions/energy-division/documents/demand-response/demand-response-workshops/advanced-der---demand-flexibility-management/joint-ious-opening-testimony-exhibit-1-errata-clean.pdf
[9] ibid.

- Reduction of non-CARE average volumetric kWh rates as described in individual IOU exhibits:
  - PG&E: From $0.34/kWh to $0.22/kWh
  - SCE: From $0.36/kWh to $0.24/kWh
  - SDG&E: From $0.47/kWh to $0.27/kWh
- Elimination of the Minimum Bill.

According to SDG&E, "a fixed pricing component to help pay for infrastructure is used throughout the U.S., including local municipal water and sewer agencies. California is one of the few states that does not include a required fixed pricing component in electric rates offered by its regulated utilities" (San Diego Gas & Electric Company, 2023).

Table II-2
Illustrative Proposed IGFCs

Income Bracket	Criteria	PG&E IGFC ($/month)	SDG&E IGFC ($/month)	SCE IGFC ($/month)
1	CARE (<= 100% FPL)	$15	$24	$15
2	All Other CARE/FERA	$30	$34	$20
3	Non-CARE/FERA <= 650% FPL	$51	$73	$51
4	Non-CARE/FERA > 650% FPL	$92	$128	$85

- Households with annual income from **$28,000 – $69,000** would pay **$20 a month** in Edison territory, **$34 a month** in SDG&E territory and **$30 a month** in PG&E territory.
- Households earning from **$69,000 – $180,000** would pay **$51 a month** in Edison and PG&E territories and **$73 a month** in SDG&E territory.
- Those with incomes **above $180,000** would pay **$85 a month** in Edison territory, **$128 a month** in SDG&E territory and **$92 a month** in PG&E territory

A3: Average Hourly Electric Emissions for 1/1/2022 from 2022 ACC

Table A3: Average hourly electric emissions from 2022 ACC

Hour Start	PG&E	SCE	SDG&E	Average
1/1/2022 0:00	0.316	0.316	0.316	0.316
1/1/2022 1:00	0.433	0.433	0.433	0.433
1/1/2022 2:00	0.428	0.428	0.428	0.428
1/1/2022 3:00	0.414	0.414	0.414	0.414
1/1/2022 4:00	0.400	0.400	0.400	0.400
1/1/2022 5:00	0.407	0.407	0.407	0.407
1/1/2022 6:00	0.393	0.393	0.393	0.393
1/1/2022 7:00	0.336	0.336	0.336	0.336
1/1/2022 8:00	0.385	0.385	0.385	0.385
1/1/2022 9:00	0.429	0.429	0.429	0.429
1/1/2022 10:00	0.405	0.405	0.405	0.405
1/1/2022 11:00	0.427	0.427	0.427	0.427
1/1/2022 12:00	0.441	0.441	0.441	0.441
1/1/2022 13:00	0.519	0.519	0.519	0.519
1/1/2022 14:00	0.480	0.480	0.480	0.480
1/1/2022 15:00	0.455	0.455	0.455	0.455
1/1/2022 16:00	0.436	0.436	0.436	0.436
1/1/2022 17:00	0.416	0.416	0.416	0.416
1/1/2022 18:00	0.394	0.394	0.394	0.394
1/1/2022 19:00	0.396	0.396	0.396	0.396
1/1/2022 20:00	0.316	0.316	0.316	0.316
1/1/2022 21:00	0.433	0.433	0.433	0.433
1/1/2022 22:00	0.428	0.428	0.428	0.428
1/1/2022 23:00	0.414	0.414	0.414	0.414
1/2/2022 0:00	0.400	0.400	0.400	0.400

A4: Annual Emissions Data Set Comparison

In order to compare ACC and WattTime data, adjustments were made to the WattTime data set to align it with the ACC data set. WattTime provides data indexed by timestamps in UTC, in 5-minute "operating interval" granularity. Timestamps were converted to PDT (UTC-7) for consistency, and hourly aggregated values were prepared. The Study Team looked at WattTime's historical dataset for the CAISO_NORTH grid subregion, in which WattTime reports its calculation for marginal operating emissions rate (MOER) (lbs CO_2 / MWh). The MOER figures were converted to units of metric tonnes (MT) (CO2 / MWh)

Figure A4-1 below shows a comparison of annual ACC data (from NP-15) and WattTime (CAISO_NORTH). NP-15 was chosen as a comparison because it most closely matches the WattTime grid subregion but note that average ACC values were used to do analysis in the rest of this study. However, there is not a significant difference between ACC NP-15 hourly average values and overall ACC hourly average values4.

Table A4-1 and Table A4-2 show a comparison of WattTime and ACC hourly emissions values. ACC emissions factors are spread out between 0 – 0.70 MT CO2/MWh while WattTime values cluster around 0.41 – 0.50 MT CO_2/MWh. This shows that annual actual grid emissions are lower than predicted by ACC in WattTime's CAISO_NORTH subregion.

Figure A4-1: ACC and WattTime Annual Emissions Data Histogram

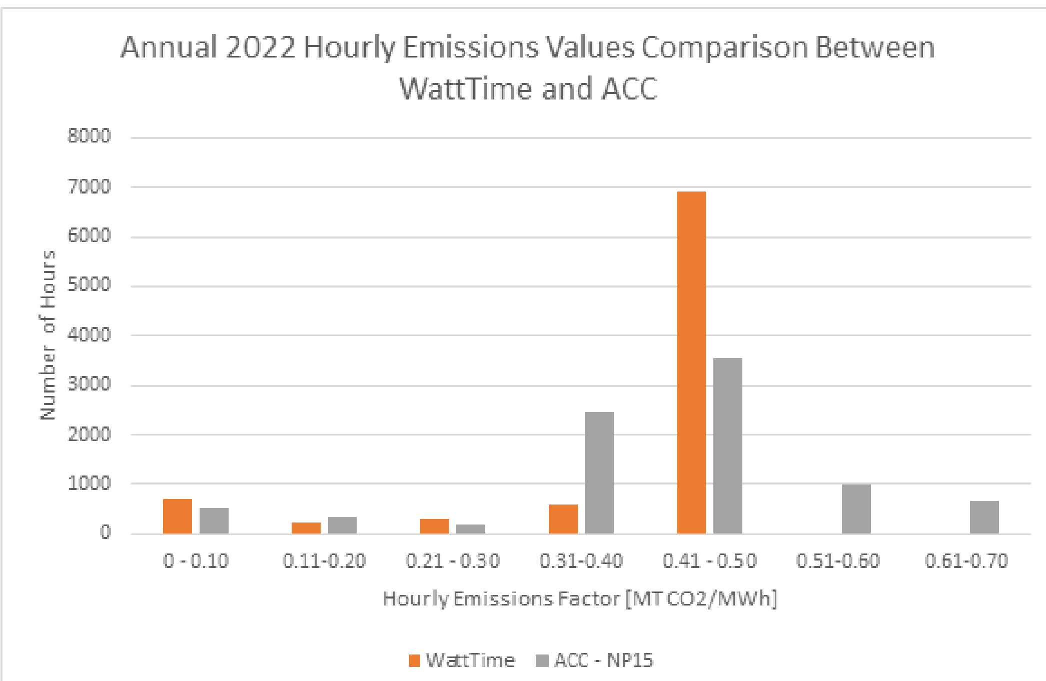


Table A4-1: WattTime and ACC Annual Emissions Values Comparison

Emissions Factor [MT CO_2/MWh]	WattTime	ACC 2022[5]
Maximum	0.499	0.663
Mean	0.379	0.403
Median	0.422	0.418
SD	0.117	0.142
Minimum	0.017	-

Table A4-2: WattTime and ACC Annual Hourly Emissions Values Frequency Comparison

Emissions Factor [MT CO_2/MWh]	No. Hours: WattTime	No. Hours: ACC - NP15
0 - 0.10	695	540
0.11-0.20	231	334
0.21 - 0.30	317	196
0.31-0.40	590	2453
0.41 - 0.50	6927	3568
0.51-0.60	0	1004
0.61-0.70	0	665

Winter Comparison

Winter emissions affect the operation of the dual fuel heating system more than the annual emissions, so an analysis was undertaken to compare only winter month emissions for both ACC and WattTime.

Table A4-3, Table A4-4, and Figure A6-5 show a summary of these values. The results are similar to the annual analysis. In winter months, WattTime also shows less emissions than predicted by ACC. The average emissions from WattTime in winter months is 0.399 MT CO2/MWh while the average predicted by ACC is 0.402 MT CO_2/MWh. Again, the median emissions factor in WattTime is higher at 0.421 MT CO_2/MWh than 0.413 MT CO_2/MWh in ACC. Lastly, the WattTime values again cluster around 0.41-0.50 MT CO_2/MWh while ACC's values are more spread out with a higher maximum emissions value. This means that the use of actual grid emissions data is unlikely to lead to a significant difference between the findings of this study that used with the ACC data.

Figure A4-2: ACC and WattTime Winter Emissions Histogram

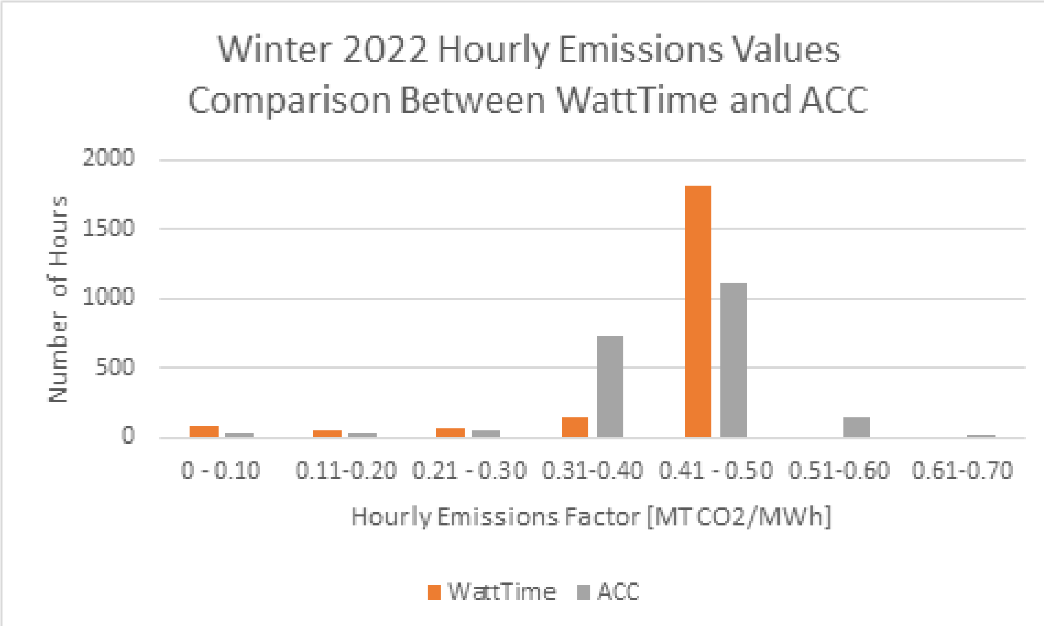


Table A4-3: WattTime and ACC Winter Emissions Values Comparison

Emissions Factor [MTCO$_2$ / MWh]	WattTime	ACC[6]
Maximum Emissions Factor	0.496	0.663
Mean Emissions Factor	0.399	0.402
Median	0.421	0.413
SD	0.090	0.088
Minimum Emissions Factor	0.021	-

Table A4-4: WattTime and ACC Winter Hourly Emissions Values Frequency Comparison

Emissions Factor [MT CO$_2$/MWh]	No. Hours: WattTime	No. Hours: ACC - NP15
0 - 0.10	81	34
0.11-0.20	49	40
0.21 - 0.30	65	60
0.31-0.40	155	738
0.41 - 0.50	1810	1118
0.51-0.60	0	143
0.61-0.70	0	27

The WattTime emissions factor profiles were added to the heating load profile and ACC emissions factor profiles to show this visually in Figure A4-3 and Figure A4-4.

It is notable that while the overall annual average emissions data from WattTime is lower than ACC predicts, the average WattTime winter emissions factors during the peak heating loads are higher than ACC.

Figure A4-3: CZ 11 Emissions Factor Profiles and Heating Load Shape

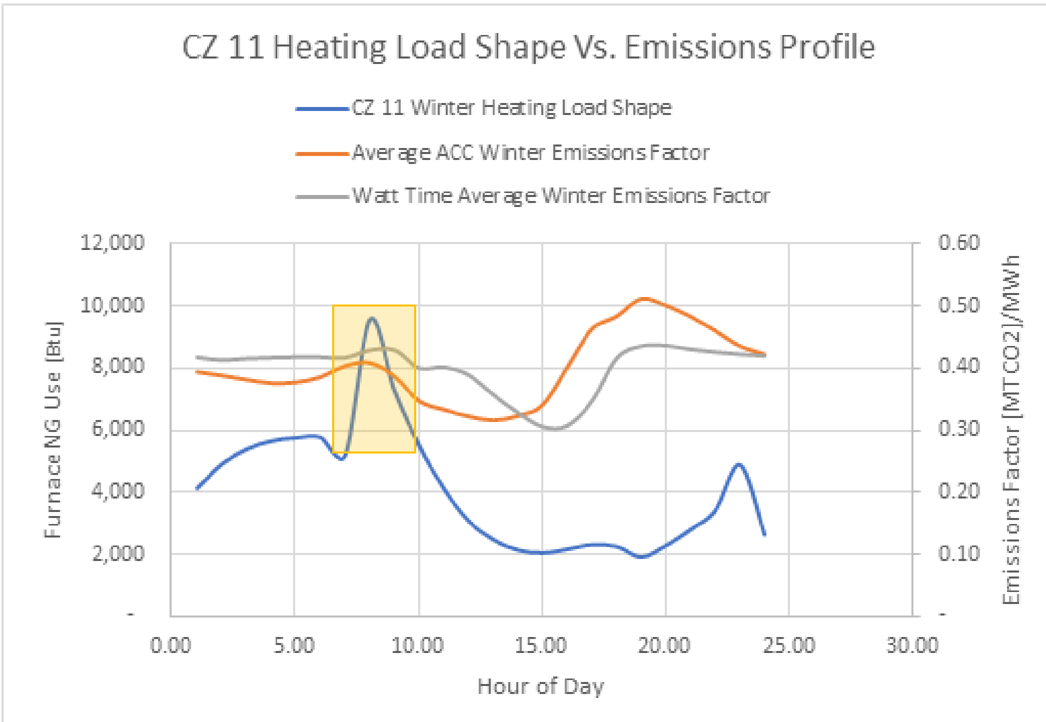
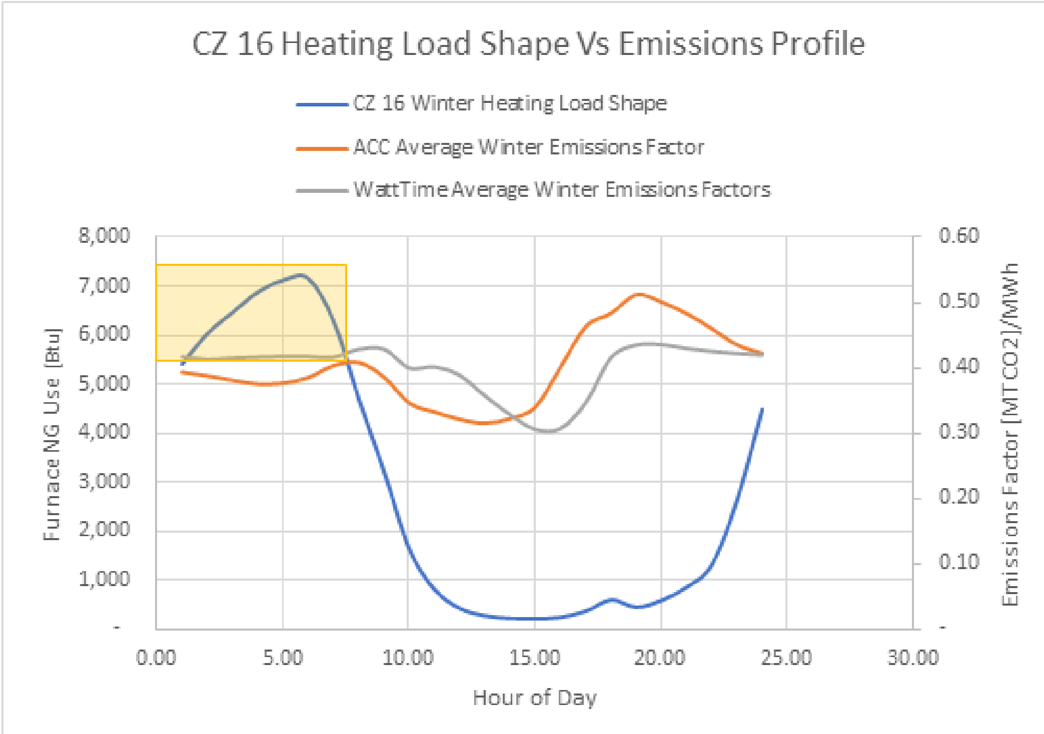


Figure A4-4: CZ 16 Emissions Factor Profiles and Heating Load Shape



Similarly, the study team investigated the annualized hourly impacts. Table A4-5 shows a comparison of the hourly average winter emissions factors for WattTime and ACC which illustrates that the ACC slightly underestimates the emissions during early morning hours, more significantly underpredicts them during the midday hours and significantly over projects them during the afternoon hours. While the mean and medians of both data sets are similar, there are significant differences in time-of-day projections. Nevertheless, the higher winter ACC emission factors do not significantly change the outcome of the preferred system as discussed at the beginning of this document.

Table A4-5: Winter Hourly Average Emissions Factors Comparison for ACC & Watt Time

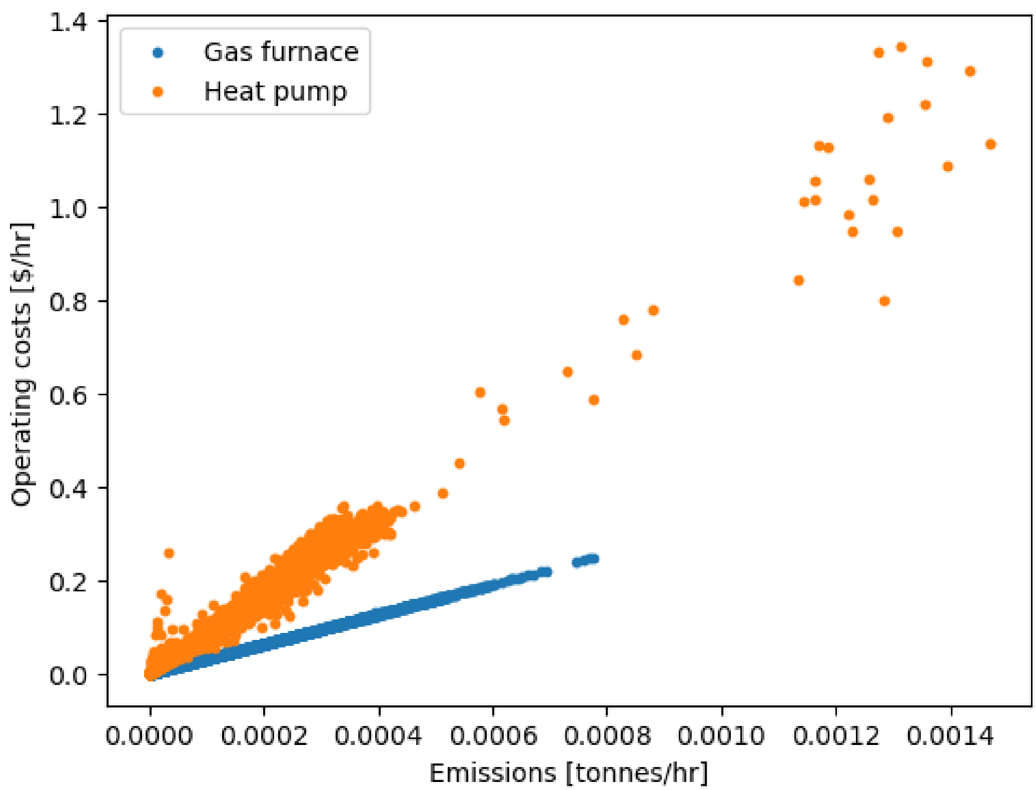
Hour of Day	2022 ACC [MT CO_2/mWh]	WattTime Emissions [MT CO2/mWh]	Percent Difference
1.00	0.394	0.416	6%
2.00	0.389	0.412	6%
3.00	0.382	0.414	8%
4.00	0.376	0.416	10%
5.00	0.378	0.417	10%
6.00	0.386	0.417	8%
7.00	0.404	0.416	3%
8.00	0.409	0.428	5%
9.00	0.387	0.428	11%
10.00	0.347	0.399	15%
11.00	0.333	0.401	20%
12.00	0.321	0.388	21%
13.00	0.314	0.356	14%
14.00	0.321	0.327	2%
15.00	0.340	0.305	-10%
16.00	0.402	0.306	-24%
17.00	0.465	0.346	-26%
18.00	0.485	0.415	-14%
19.00	0.513	0.434	-15%
20.00	0.502	0.435	-13%
21.00	0.484	0.429	-11%
22.00	0.461	0.425	-8%
23.00	0.436	0.421	-3%
24.00	0.423	0.419	-1%

A5: Scatter Plots

Combined Impacts for Potential Controller Programming

Putting together all the key variables of heating equipment efficiencies, weather sensitive equipment, unit energy prices, and emissions factors we begin to have the whole picture. Figure A5-1 shows the scatterplot trend of hourly operating costs vs emissions for each heating system (solo furnace and solo heat pump).

Figure A5-1: Hourly trend data, CZ 16, flat rate electric tariff.



For a comparison between gas furnace and electric heat pump, Figure A5-2 shows the trend for changes in both emissions and operating costs for each hour.

Figure A5-2: Hourly trend data, changes in costs and emissions, CZ 16, flat rate.

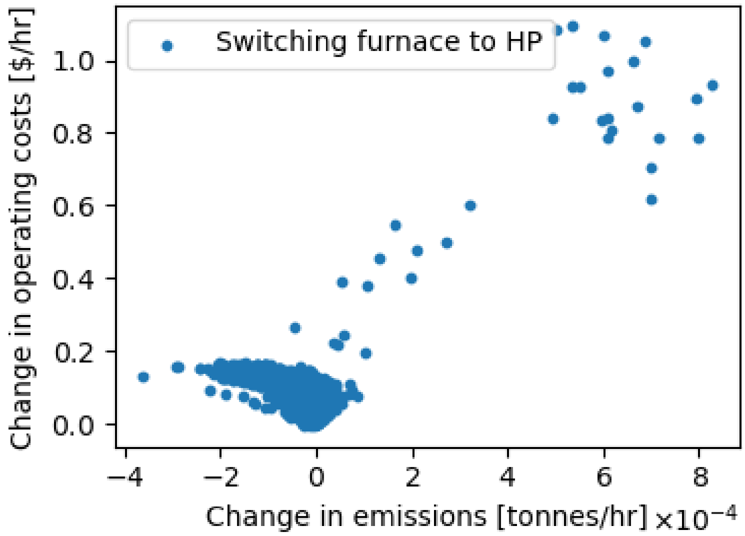


Figure A5-3 and Figure A5-4 are histograms showing frequency of occurrence of hourly variable values for switching from furnace operation mode to heat pump operation mode. Distributions of GHG emissions change and operating cost changes are multimodal, with multiple peaks. The resulting emissions change per unit cost increase is not a normal (Gaussian) distribution but is skewed with most hours having low emissions saving potential. This metric (emissions change per unit cost increase) indicates the degree to which allocating budget to heat pump operation will save emissions in each hour. The following figures are based on flat rate electric tariffs and the single-family home model described above.

Figure A5-3: Histogram, hourly operating cost differential, CZ 16, flat rate tariff.

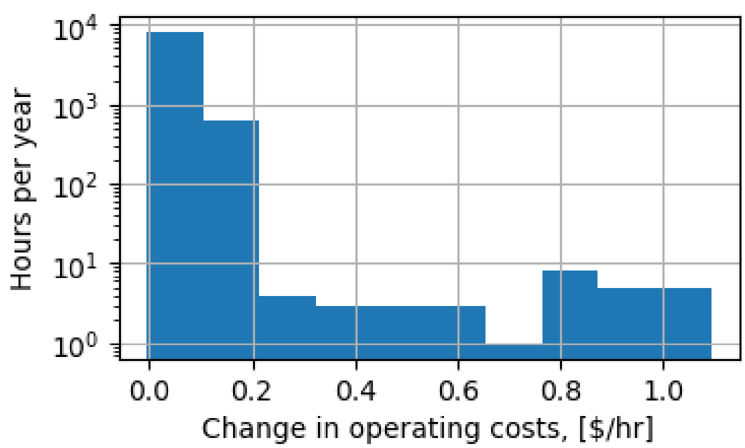


Figure A5-4: Histogram, hourly emissions differential, CZ 16.

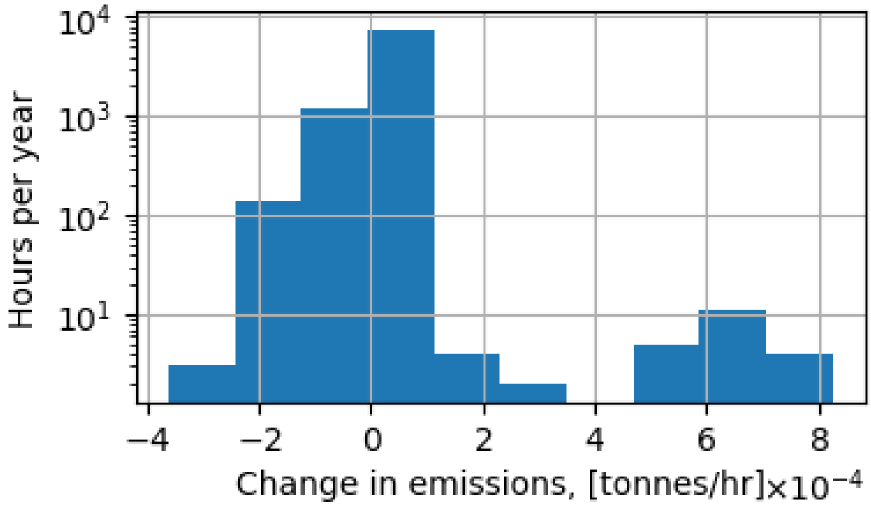
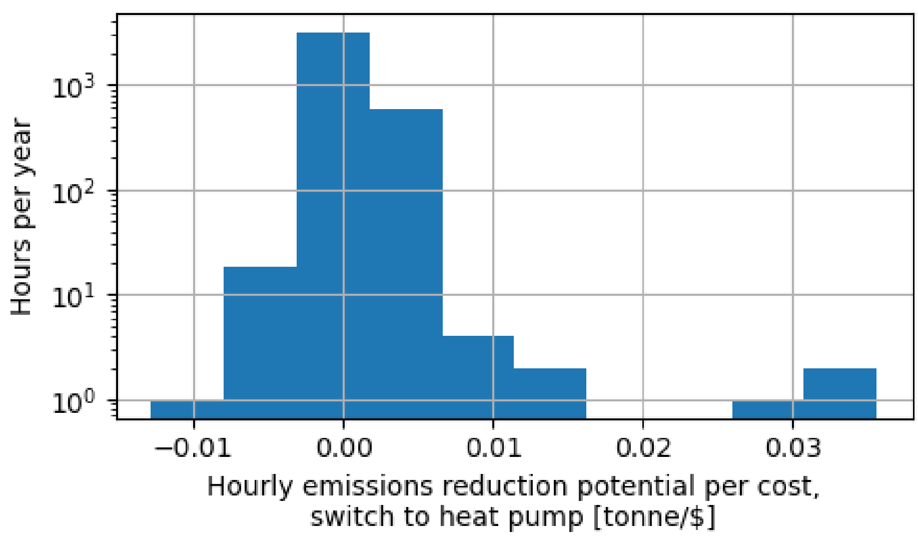


Figure A5-5: Histogram, emissions per unit cost differential, CZ 16.



Figures A5-6 to A5-9 below show similar results for other pairings of climate zone and rate plan that were considered.

Figure A5-6: Histogram, emissions per unit cost differential, CZ 16, TOU tariff.

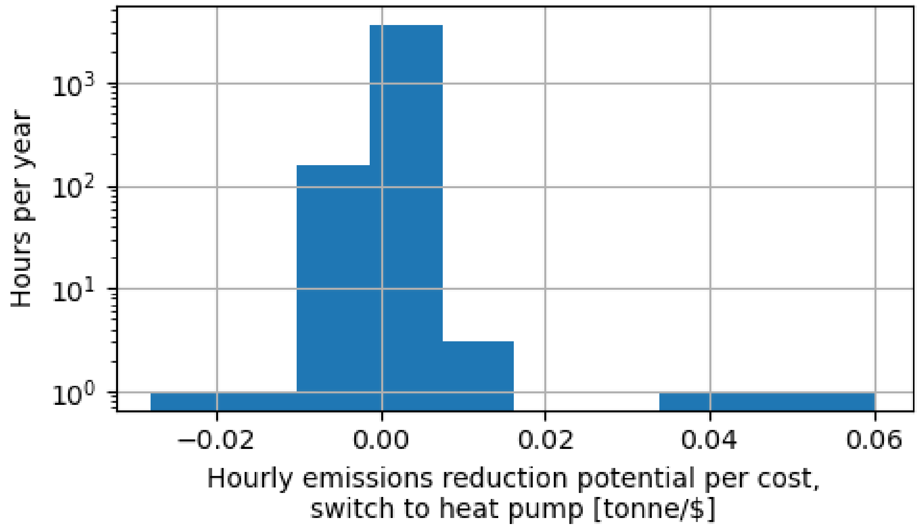


Figure A5-7: Hourly trend, cost and emissions differentials, CZ 11, flat rate tariff.

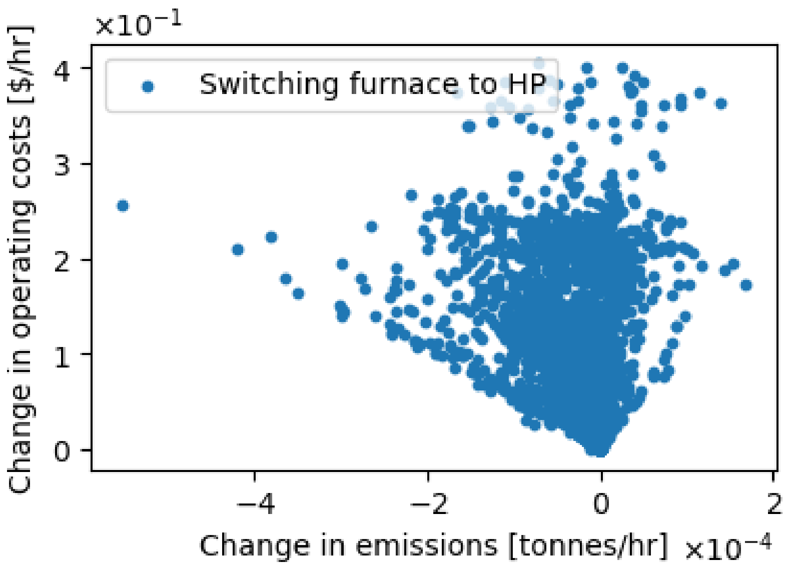


Figure A5-8: Histogram, emissions per unit cost differentials, CZ 11, flat rate tariff.

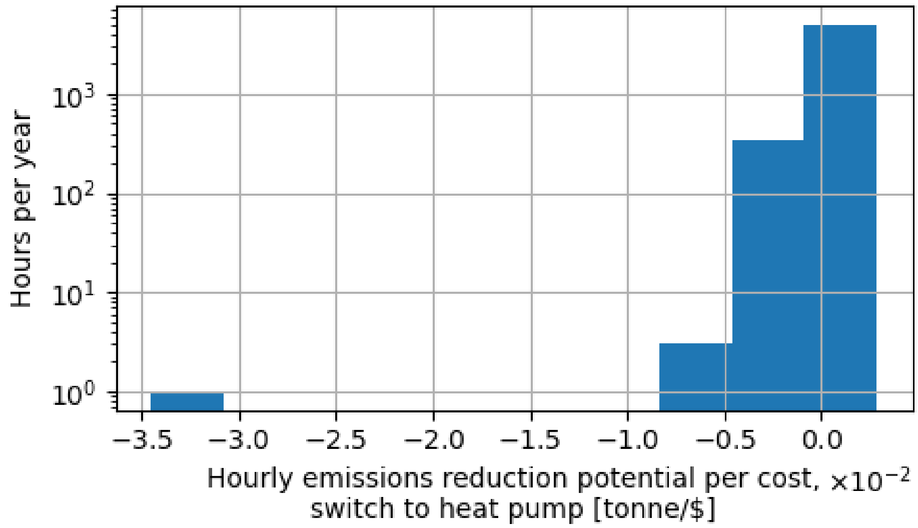


Figure A5-9: Histogram, emissions per unit cost differentials, CZ 11, TOU electric tariff.