CALIFORNIA ENERGY COMMISSION

Energy Research and Development Division

FINAL PROJECT REPORT

Demonstration of Advanced High-Efficiency, Low-Capacity HVAC Systems

May 2023 | CEC-500-2023-024

PREPARED BY:

Primary Authors:

Kaushik Biswas, PhD
Robert Kamisky

Kristin Heinemeier, PhD
Stephen Chally

Gas Technology Institute
123 C Street, Davis, CA 95616
Phone: 530-324-6059
http://www.gti.energy

Frontier Energy
123 C Street, Davis, CA 95616
Phone: 530-316-1820
https://frontierenergy.com/

Contract Number: PIR-16-002

PREPARED FOR:
California Energy Commission

Abigail Jacob
Project Manager

Virginia Lew
Office Manager
Energy Efficiency Research Office

Jonah Steinbuck
Deputy Director
ENERGY RESEARCH AND DEVELOPMENT DIVISION

Drew Bohan
Executive Director

ACKNOWLEDGEMENTS

The authors thank Eric Stubee, Yuval Edrey, Erin Bonetti and Luke Bingham of GTI for their assistance with utility data analysis, BEopt energy modeling and reviewing the report, and James Haile, Peter Holderbein and Josh McNeil of Frontier Energy for their assistance with monitoring instrumentation and decommissioning. The project team also thanks Dan Mort of ADM Associates, Inc. for reviewing and providing feedback on the analysis methods and results. And finally, the project team thanks Larry Brand of Frontier Energy for proposing this research and his guidance and mentorship throughout the project.

PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division manages the Natural Gas Research and Development Program, which supports energy-related research, development, and demonstration not adequately provided by competitive and regulated markets. These natural gas research investments spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution, and transportation.

The Energy Research and Development Division conducts this public interest natural gas-related energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public and private research institutions. This program promotes greater natural gas reliability, lower costs and increases safety for Californians and is focused in these areas:

- Buildings End-Use Energy Efficiency.
- Industrial, Agriculture and Water Efficiency
- Renewable Energy and Advanced Generation
- Natural Gas Infrastructure Safety and Integrity.
- Energy-Related Environmental Research
- Natural Gas-Related Transportation.

Demonstration of Advanced High-Efficiency, Low Capacity HVAC Systems is the final report for the Demonstration of Advanced High-Efficiency, Low Capacity HVAC Systems project (PIR-16-002) conducted by the Gas Technology Institute. The information from this project contributes to the Energy Research and Development Division's Natural Gas Research and Development Program.

For more information about the Energy Research and Development Division, please visit the CEC's research website (www.energy.ca.gov/research/) or contact the CEC at 916-327-1551.

ABSTRACT

This project demonstrated the energy and comfort-related performance of high-efficiency, low-capacity heating, ventilation, and air conditioning (HVAC) systems which replaced existing HVAC systems in five single-family homes located in Los Angeles and Orange County. The five test houses also received envelope upgrades, which included additional attic and duct insulation and air sealing.

The project team collected utility data from the test homes before and after the envelope retrofits and HVAC replacement. The team also performed building energy modeling to support the utility data analysis. The analysis and modeling results indicated that the envelope and HVAC upgrades can reduce the HVAC energy consumption by 30 percent or more in the demonstration homes.

The project team monitored the low-capacity HVAC systems over two winters and summers, tracking and analyzing comfort conditions within the houses and parameters like cycling, runtime, energy consumption and energy delivered. Occupant surveys concluded that all homeowners were more comfortable with the new HVAC system, indicating few or no comfort-related issues and even providing better comfort.

Estimated ratepayer benefits from the envelope and HVAC upgrades include average annual savings of 880,786 therms of natural gas and 6.4 GWh of electricity, with associated annual cost savings of $1,300,709 for natural gas and $1,277,220 for electricity. The avoided cumulative carbon dioxide emissions in the next five years would be up to 33,910 metric tons, and NOx emissions avoided would be up to 12.1 metric tons.

Keywords: envelope upgrades; furnace; high-efficiency, low capacity HVAC; right sizing HVAC; attic insulation; buried ducts; duct sealing

Please use the following citation for this report:

Biswas, Kaushik, Kristin Heinemeier, Stephen Chally, Robert Kamisky. 2021. *Demonstration of Advanced High-Efficiency, Low Capacity HVAC Systems*. California Energy Commission. Publication Number: CEC-500-2023-024.

TABLE OF CONTENTS

Page

LIST OF FIGURES

Page

LIST OF TABLES

EXECUTIVE SUMMARY

Introduction or Background

California aims to improve the efficiency of its buildings to accomplish its statewide target of reducing 40 percent of greenhouse gas emissions below the 1990 level by 2030. To maximize the benefits of upgraded building envelopes (the exterior or shell of a building that includes doors and windows, roofs, walls and insulation) and reduced space conditioning loads in existing homes' heating, ventilation, and air conditioning (HVAC) systems that are optimized for lower thermal loads are required.

Standard practice for sizing HVAC equipment involves a design calculation based on home parameters and weather, followed by the application of a capacity multiplier to cover peak loads. As such, larger than necessary HVAC systems are often used, which can lead to overheating and overcooling. Conversely, a low-capacity HVAC system is expected to follow the home's load more precisely. The result is lower energy use while maintaining occupant comfort.

This project combined envelope improvements, such as air sealing and attic insulation upgrades, with an advanced low-capacity HVAC system to demonstrate their energy saving potential together. The HVAC systems selected for this demonstration were 1/3 to 1/2 the size of standard HVAC systems that were replaced, offer very high-efficiency ratings, and meet the current ultra-low-NOx requirements of the South Coast Air Quality Management District (SCAQMD). Five homes in Los Angeles and Orange County were selected as the demonstration sites for this project.

Project Purpose

This project funded field demonstration and performance testing of advanced high-efficiency, low-capacity HVAC systems coupled with measures to reduce infiltration and improve building envelopes in five existing single-family homes. This team, from the Gas Technology Institute (GTI) and Frontier Energy, both located in Davis, California sought to combine building envelope improvements with advanced low-capacity HVAC systems to demonstrate system-level energy saving opportunities.

The goal was to achieve HVAC energy savings of more than 30 percent compared to a typical, existing Los Angeles Basin house with standard equipment. The demonstration sites were located in California climate zones 6, 8, and 9. These warm coastal climates, centered in Los Angeles and Orange counties, are characterized by low heating loads and moderate cooling loads. Five houses, one each in Costa Mesa, Covina, Lake Forest, Northridge and Rancho Palos Verdes, were retrofitted and monitored for about 24 months. The team then performed analyses of field and utility billing data, in addition to building energy modeling, to establish the energy savings.

Project Approach

The project team retrofitted the houses with new two-stage furnaces from Lennox, which met the SCAQMD's ultra-low-NOx emissions standard, and a seasonal energy efficiency ratio 16 1.5-2 ton two-stage condensing unit. The team also fitted the homes with Ecobee web-connected thermostats.

All demonstration site houses were single-story, standard wood-framed, slab-on-grade, ranch-style single-family with vented attics, and built between 1951 and 1976 with living areas of 1,356 to 1,779 square feet. The audit of the selected houses included evaluating the building envelope and duct systems. The team noted key construction characteristics and performed blower door and duct blaster diagnostic tests to determine air infiltration to conditioned space and duct leakage to unconditioned space. Based on the audits, all the houses received some envelope and/or duct upgrades, in addition to the HVAC replacement.

The overall data collection, measurements and analysis methods consisted of: (1) utility data collection and analysis, (2) building energy modeling, and (3) site testing and data monitoring. The team obtained utility data from all the test houses for the pre-retrofit and post-retrofit periods. The project team analyzed the utility data to estimate the reductions in the HVAC energy use resulting from the envelope upgrades and installation of the high-efficiency, low-capacity Lennox system. The project team also conducted tests in the houses to better understand how well they can recover from temperature setbacks and pre-cooling.

Finally, the project team interviewed several stakeholders, including HVAC installation contractors, building science experts, and equipment manufacturers, to identify what they felt were the most interesting findings and implications from this research.

Project Results

The results of the aggregate utility data comparison from the pre-retrofit and post-retrofit periods showed an average reduction of 33 to 38 percent in gas use for heating and 43 to 48 percent in electricity use for cooling when compared to prior years. Calibrated energy models were developed to support the utility data analysis and the model results indicated average heating and cooling energy savings of 44 percent and 31 percent, respectively, compared to the baseline existing homes.

Data from the field monitoring showed that the low-capacity HVAC systems were able to meet the heating and cooling needs of the houses. On the survey questionnaire, homeowners had few or no comfort-related issues with the high efficiency system compared to the prior HVAC systems. These results indicated that low-capacity systems can even provide better comfort. Regarding runtimes, the homeowners perceived the low-capacity system ran for the "right amount of time", while their old system ran "too long." This was counterintuitive since one would expect the low-capacity system to follow the heating and cooling loads more precisely, and consequently run longer than the typically oversized systems. One explanation is that the low-capacity system is much quieter - a response also noted by many survey respondents - so the *perceived* runtime is less. These results indicated that occupants did not object to or find troublesome the increased runtime of the low-capacity system.

Pre-cooling tests in two homes indicated that the houses were successful at shifting cooling loads before the peak for the electric grid, 4 – 9 PM. However, both homes consumed more total cooling energy, primarily during off-peak hours, compared to the days before the pre-cooling tests. This suggests that limiting precooling to days with high expected on-peak cooling loads would maximize energy and peak savings.

Technology/Knowledge Transfer/Market Adoption (Advancing the Research to Market)

The project team will make the information from the report publicly available from the California Energy Commission and GTI websites. The team has shared project results with HVAC professionals, homeowners, program managers, and others regarding retrofit measures and low-capacity, high-efficiency HVAC performance. The team also held a public webinar on August 25, 2021, with 27 attendees from eleven organizations. The project team intends to present the project findings at the Buildings XV Conference. Furthermore, the GTI website will host a sub-website dedicated to sharing the results of this project at https://www.gti.energy/lowcapacityhvac/.

Benefits to California

The project team calculated cumulative energy savings, emission reductions and cost savings for new and retrofit markets. According to the Construction Industry Research Board [2019], more than 6.4 million single family homes were built in California between 1954 and 2019. For the retrofit market, it is assumed that one out of fifteen single family homes will replace their HVAC systems each year and upgrade the attics and ducts.

Starting with the 2019 Contruction Industry Research Board projection and assuming a 10 percent increase, the team estimated 394,504 new houses will be built between 2021 and 2025. For retrofit and new construction markets, the team assumed a growing market share of 2 to 10 percent between 2021 and 2025 for low-capacity HVAC systems and envelope upgrades.

The team assumed a 30 percent reduction in heating and cooling energy consumption for the retrofit market based on the project goal and a 17 percent reduction in heating energy consumption for new construction based on additional modeling.

The calculation results showed average annual energy savings of 880,589 therms of natural gas and 6.4 GWh of electricity. The estimated cumulative annual cost savings were $1,300,418 for natural gas and $1,277,220 for electricity. On a per household basis, the average annual savings for existing homes was estimated to be $166. The projected cumulative CO_{2e} emissions avoided during 2021-2025 is 33,905 metric tons, and NOx emissions avoided due to reduced heating energy use is 12.1 metric tons.

CHAPTER 1: Introduction

New residential buildings in California continue to become more energy efficient, driven by Title 24, Part 6 energy code requirements. Additionally, California Senate Bill 32 (Pavley, Chapter 249, SEC. 2) has set a target of a 40 percent reduction in statewide greenhouse gas emissions below the 1990 level by 2030.[1] As a result, there is increased awareness and a general drive towards improving the performance of existing single-family residential buildings.

To maximize the benefits of more energy efficient building envelopes and consequently lower space conditioning loads, heating, ventilation, and air conditioning (HVAC) systems that are optimized for lower thermal loads are needed. Standard practice for sizing HVAC equipment is to perform a design calculation based on home parameters and weather and then apply a capacity multiplier to cover peak loads. American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE) standard 103[2] uses a capacity multiplier of 1.7 for testing purposes. Often, larger HVAC systems than necessary for the house load are used, which can lead to overheating and overcooling the space. A low-capacity HVAC system is expected to follow the home's load more precisely. The result is lower energy use while maintaining occupant comfort. This project sought to combine envelope improvements with advanced low-capacity HVAC systems to demonstrate system-level energy saving opportunities.

The goal of this California Energy Commission (CEC) grant was to demonstrate that measured envelope retrofits coupled with high-efficiency, low-capacity HVAC systems in existing single-family homes will show energy savings of more than 30 percent compared to a typical Los Angeles Basin existing home with standard equipment. Similar savings are expected from combining high-efficiency, low-capacity HVAC systems with above-code practices in new construction. In this report, "low capacity" relates to HVAC equipment sized for low-load homes – furnaces below 40 kBtu/h and air conditioning (AC) systems below two tons or 24 kBtu/h of cooling capacity. While the primary focus of the project is quantifying natural gas savings for California's natural gas ratepayers, the project also quantifies additional benefits such as electricity savings and comfort improvements.

The demonstration sites were located in California climate zones 6, 8, and 9. These warm coastal climates, located in Los Angeles and Orange counties, are characterized by low heating loads and moderate cooling loads. Five homes received the retrofits and

---

[1] https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201520160SB32

[2] https://webstore.ansi.org/standards/ashrae/ansiashrae1032017

were monitored for about 24 months. Field and utility billing data were analyzed and compared with baseline energy consumption from previous years' energy bills to establish energy savings. The project sought to determine if the high-efficiency, low-capacity system combined with envelope upgrades will provide energy savings while meeting thermal loads and comfort requirements in these climate zones.

The low-capacity system selected for this demonstration was a 40 kBtu/h, 97.5 percent annual fuel utilization efficiency (AFUE), two-stage, ultra-Low-NOx-compliant system from Lennox. In its low-fire stage, the furnace gets down to a minimum input capacity of 26 kBtu/h, which is much smaller than most furnaces typically installed in California. In the low fire stage, the efficiency is 96.15 percent, based on the furnace output specification of 25 kBtu/h. The two-stage furnace creates an interesting research opportunity to simulate either a 26 kBtu/h single-stage furnace, a 40 kBtu/h single-stage furnace, or a 40 kBtu/h two-stage furnace depending on controls configuration. The Lennox furnace was paired with a two-stage AC unit with a seasonal energy efficiency ratio (SEER) of 16. The AC unit had a low-stage capacity of 1.5 ton and a high-stage capacity of 2 ton.

The project team identified five homes in the Los Angeles metropolitan area to be suitable demonstration sites for the low-capacity furnace project. Table 1 lists the locations of the five homes, including city and zip code, and the letter codes used to address them in the rest of this report.

Table 1: Test Home Locations and Letter Codes

City	ZIP code	Letter code
Costa Mesa	92627	CMJ
Covina	91724	CVC
Lake Forest	92630	LFS
Northridge	91324	NRB
Rancho Palos Verdes	90275	RPS

Source: Gas Technology Institute

CHAPTER 2: Project Approach

Technology Description – Low-Capacity HVAC

The project team retrofitted all the homes with new 40 kBtu/h 2-stage furnaces from Lennox meeting the 14 ng/J NOx emissions standard, and a SEER 16 2-ton two-stage condensing unit. AC units were paired with ADP LC42/49K9BG coils (Figure 1). In addition, Ecobee web-enabled thermostats were installed in all homes. Lennox furnace and air conditioner specifications are listed in Table 2 and Table 3.

Table 2: Lennox Furnace Specifications

Model	59SC5A026S14
Height	33"
Depth	29.75"
Width	17.5"
Rated Input	40,000 Btu/h high fire; 26,000 Btu/h low fire
AFUE	97.5% AFUE
Airflow	440-1370 CFM
Motor	1/2 HP ECM
Emissions	Ultra-Low NOx (14 ng/J)

Source: Lennox

Table 3: Lennox Air Conditioner Specifications

Model	XC16-024
Refrigerant	R410A
Height	45”
Depth	35”
Width	30.5”
Rated Capacity	2-ton high stage; 1.5-ton low stage
SEER	16
EER	13

Source: Lennox

Figure 1: Lennox Low-Capacity, Ultra-Low NOx Furnace at NRB

Source: Gas Technology Institute

Demonstration Sites

Table 4 lists the general size descriptors, vintage and climate zone designation of the homes. All houses are single-story, standard wood framed, slab-on-grade, ranch-style single-family homes with vented attics.

Table 4: Test Home Size, Vintage and Climate Zones

Site	Area, ft^2	Bed / Bath	# Occupants	Vintage	California Climate Zone
CMJ	1,432	3 / 2	2	1951	Zone 6
CVC	1,650	4 / 2.5	2	1964	Zone 9
LFS	1,356	3 / 2	1-2	1976	Zone 8
NRB	1,460	4 / 2.5	3 – 5	1960	Zone 9
RPS	1,779	3 / 2	1-2	1954	Zone 6

Source: Gas Technology Institute

Energy Efficiency Measures

The audit of the selected homes included an evaluation of the building envelope and the duct systems. The project team noted key construction characteristics, and performed blower door and duct blaster diagnostic tests to characterize air infiltration to conditioned space and duct leakage to unconditioned space. The home audit indicated that all the homes required upgrades to the envelope and duct systems. Thus, in addition to the HVAC replacement, some envelope and duct system upgrades were performed in most homes, which are described in the following sub-sections. The HVAC and envelope characteristics of the different homes before and after the efficiency upgrades are also described below.

Site CMJ

This home received a well-executed home energy retrofit in 1992 and thus did not require many incremental measures within the current project. It received additional attic insulation to bury the ducts along with the new, low-capacity HVAC equipment. This home did not previously have air conditioning, but to have consistent equipment at all the sites and because this would be a typical addition during a furnace replacement, the same Lennox AC unit was also installed at the other sites. Table 5 lists the pertinent pre-retrofit and post-retrofit building characteristics. The air leakage rates are listed as ACH 50 or air changes per hour at 50 Pascal pressure differential across the building envelope.

Table 5: Building Characteristics - CMJ

	Pre-retrofit	Post-retrofit
Furnace Capacity/Efficiency	75 kBtu/h, 80% AFUE	26 kBtu/h, 96.15% AFUE 40 kBtu/h, 97.5% AFUE
AC Capacity/Efficiency	No AC	1.5 tons, 16 SEER / 2 tons, 16 SEER
Wall Insulation	R-13 Blown Cellulose	R-13 Blown Cellulose
Foundation Insulation	None	None
Roof/Attic Insulation	R-30 Cellulose degraded to R-19	R-38 Cellulose
Air Leakage (ACH50)	8.5	8.5
Duct Location, Insulation	Attic, R-4.2	Attic, R8 buried ducts
Duct Leakage	0% leakage to outside	0% leakage to outside

Source: Gas Technology Institute

Site CVC

This site already had a good duct system and enclosure, so retrofits were restricted to installing the low-capacity HVAC system and adding attic insulation to achieve buried ducts. Table 6 lists the pre- and post-retrofit building characteristics.

Table 6: Building Characteristics - CVC

	Pre-retrofit	Post-retrofit
Furnace Capacity/Efficiency	75 kBtu/h, 81% AFUE	26 kBtu/h, 96.15% AFUE 40 kBtu/h, 97.5% AFUE
AC Capacity/Efficiency	4 tons, 12 SEER	1.5 tons, 16 SEER / 2 tons, 16 SEER
Wall Insulation	R-11	R-11
Foundation Insulation	None	None

Roof/Attic Insulation	Vented Attic, R-30	R38
Air Leakage (ACH50)	7.5	7.5
Duct Location, Insulation	Attic, R-4	Attic, R8 buried ducts
Duct Leakage	59 CFM25 to outside	59 CFM25 to outside

Source: Gas Technology Institute

Site LFS

At this house, a leaky duct system and enclosure were addressed by air sealing the attic plane and replacing the attic ducts. The existing duct system had asbestos insulation, so it was remediated as part of the scope. Due to remaining asbestos insulation in inaccessible portions of the duct system, the contractor decided not to test duct leakage or whole house leakage post-retrofit. The project team also replaced an existing atmospheric water heater too close to an HVAC return installed in a laundry room with a new direct-vent model to avoid combustion safety concerns. The envelope upgrades included R-38 attic insulation and buried ducts. The results are shown in Table 7.

Table 7: Building Characteristics - LFS

	Pre-retrofit	Post-retrofit
Furnace Capacity/Efficiency	80 kBtu/h, 95.5% AFUE	26 kBtu/h, 96.15% AFUE 40 kBtu/h, 97.5% AFUE
AC Capacity/Efficiency	3 tons, 16 SEER	1.5 tons, 16 SEER / 2 tons, 16 SEER
Wall Insulation	R-11	R-11
Foundation Insulation	None	None
Roof/Attic Insulation	R-11 Grade 3; R-4 equivalent	R38
Air Leakage (ACH50)	13	Not tested; 13 assumed
Duct Location, Insulation	Attic, R2.1	Attic, R8 buried ducts
Duct Leakage	422 CFM to outside	Not tested; 15% assumed conservatively

Source: Gas Technology Institute

Site NRB

In addition to the HVAC equipment, this site received a new duct system with R8 insulation and R-38 attic insulation to achieve fully buried ducts. A small area was uncovered right around the furnace itself, where it was not possible to have all the ducts lie flat on the attic floor joists. As shown in Table 8, attic duct replacement also resulted in less overall duct leakage. An error was made during the post-retrofit air exchange rate testing, so no results were available. No major air sealing was required or performed at the site, so the air exchange rate is listed as "unchanged," however, some improvement is expected due to the decreased leakage of the new duct system.

Table 8: Building Characteristics - NRB

	Pre-retrofit	Post-retrofit
Furnace Capacity/Efficiency	75 kBtu/h, 78% AFUE	26 kBtu/h, 96.15% AFUE 40 kBtu/h, 97.5% AFUE
AC Capacity/Efficiency	3.5 tons, 10 SEER	1.5 tons, 16 SEER / 2 tons, 16 SEER
Wall Insulation	None	None
Foundation Insulation	None	None
Roof/Attic Insulation	R-11 Fiberglass	R-38 Cellulose
Air Leakage (ACH50)	11.3	10.0 assumed
Duct Location, Insulation	Attic, R8	Attic, R8 buried ducts
Duct Leakage	30% total leakage	9% total leakage

Source: Gas Technology Institute

Site RPS

This site still featured the original 1950s furnace and tested as extremely leaky pre-retrofit. Therefore, existing attic insulation was removed to perform air sealing at the attic plane and the existing attic duct system was replaced. The team discovered during the job that pre-existing wall ducts had asbestos insulation, so, the duct system and envelope were not pressure-tested post-installation. This home also did not have an air conditioner pre-retrofit, so the low-capacity Lennox AC unit was installed. Results are shown in Table 9.

Table 9: Building Characteristics - RPS

	Pre-retrofit	Post-retrofit
Furnace Capacity/Efficiency	125 kBtu/h, estimated 60% AFUE	26 kBtu/h, 96.15% AFUE 40 kBtu/h, 97.5% AFUE
AC Capacity/Efficiency	No AC	1.5 tons, 16 SEER / 2 tons, 16 SEER
Wall Insulation	R-11	R-11
Foundation Insulation	None	None
Roof/Attic Insulation	R-32	R-38
Air Leakage (ACH50)	32	Not tested; 32 assumed
Duct Location, Insulation	Attic, R4.2	Attic, R8 buried ducts
Duct Leakage	40% total leakage	Not tested; 0% to outside assumed

Source: Gas Technology Institute

Data Acquisition and Analysis Methods

This section describes the overall data collection, measurements, and analysis methods, which can be categorized as follows:

1. Utility data collection and analysis.
2. Building energy modeling.
3. Site testing and data monitoring.

Utility Data Analysis

The project team obtained utility data from all the test homes for both the pre-retrofit as well as the post-retrofit period. The data was available since 2016 for CVC and LFS, since 2017 for NRB and RPS, and since 2018 for CMJ. The data was analyzed to estimate the reductions in the HVAC energy use resulting from the envelope upgrades and installation of the high-efficiency, low-capacity Lennox system.

Raw Utility Data

The project team plotted and compared the raw monthly or periodic data for natural gas, in therms, and electricity, in kWh, for the prior and post-retrofit periods. One of the sites, LFS, has on-site photovoltaics, but the project team did not consider the generation data as part of this project, with the focus being on energy consumption. Based on the utility data from LFS, the site had photovoltaics since before 2016.

Estimation of HVAC Energy Consumption

To estimate the HVAC energy consumption from the raw utility data, the project team calculated the baseline gas and electric energy consumption for all years and all sites. Based on past work done by Frontier Energy, it was assumed that water heating was responsible for 67 percent of the baseline gas consumption and the remaining 33 percent was attributed to miscellaneous appliances such as clothes dryers, cooking ranges, and so on. Further, the project team assumed the gas consumption for water heating to be a function of the monthly entering water temperature to the homes, which is approximated using monthly water heater (WH) multipliers listed in Table 10.

Table 10: Monthly WH Multipliers

Month	WH multiplier (WHM)
Jan	1.97
Feb	1.66
Mar	1.41
Apr	1.22
May	1.08
Jun	1.00
Jul	0.97
Aug	1.01
Sep	1.10
Oct	1.25
Nov	1.45
Dec	1.71

Source: Frontier Energy

First, the project team calculated the mean gas consumption (M_5) from the five summer months with the lowest gas use, with the expectation that no space heating is required during those months. The variable gas baseline, $B_{gas,var}$, was calculated as:

$$B_{gas,var} = (WHM*0.67+0.33)*M_5 \quad (1)$$

For the baseline electricity consumption, the team plotted the monthly kWh values against the calculated cooling degree days (CDD) and extrapolated to CDD = 0 to estimate the baseline consumption; the assumption being that at zero CDD, no cooling is needed. For sites where no clear correlation was observed between monthly kWh values and CDD, the average of the lowest five months of consumption during each year was used.

Heating and Cooling Degree Day Analysis

To better understand the HVAC energy consumption, the team normalized the estimated gas and electricity consumption for heating and cooling by the respective heating degree days (HDD) and CDD. For calculating HDD and CDD values, the team determined the degree day base temperature by calculating the best fit regression line of hourly heating or cooling energy consumed versus hourly outdoor temperatures from nearby weather stations. The base temperature was the temperature at which the regression line crossed the line of zero energy use. Table 11 lists the weather stations associated with each site.

Table 11: Weather Stations

Site	**CMJ**	**CVC**	**LFS**	**NRB**	**RPS**
Weather station (WMO #)	Santa-Ana-John-Wayne-AP (722977)	Brackett (722887)	Santa-Ana-John-Wayne-AP (722977)	Van-Nuys-AP (722886)	Torrance-Muni-AP (722955)

Source: Gas Technology Institute

Finally, to estimate energy savings based on utility data and compare against the project goal of 30 percent reduction in HVAC energy use, the team calculated aggregate energy consumption for heating and cooling during the winter and summer months, respectively, for the different years. The savings were based on estimated HVAC consumption, that is raw utility data less baseload and normalized by the respective HDD or CDD values. The savings were calculated against two baselines – first, the average of the heating energy use from the winter periods before the low-capacity HVAC system installation when the data was available, that is 2018-19 and earlier, and second, the previous "clean" winter period, when there were no known anomalies in the gas consumption. Similarly, the team calculated the savings for cooling electricity consumption during summer. The team assumed winter periods comprised of November through February, and summer periods were June through September.

Building Energy Modeling

The team used energy modeling to support the utility data analysis for estimations of energy savings. It is noted that weather normalization of utility, as described in the previous section, cannot account for occupant behavior on energy consumption. Thus, building energy models were created and calibrated against utility data. The calibrated models were then used to estimate the energy performance of the homes before and after the envelope retrofits and HVAC replacement under a common set of weather and operating conditions.

Modeling Overview

For this project, the team chose BEopt version 2.8.0.0[3] as the modeling tool. The BEopt software provides capabilities to evaluate residential building designs and identify cost-optimal efficiency packages for various levels of whole-house energy savings. BEopt can be used to analyze new construction and existing home retrofits, as well as single-family detached and multi-family buildings, through evaluation of single building designs, parametric sweeps, and cost-based optimizations. BEopt provides detailed simulation-based analysis based on specific building characteristics, such as size, architecture, occupancy, vintage, location, and utility rates. Discrete envelope and equipment options, reflecting realistic construction materials and practices, are evaluated.

In BEopt, a user can select from predefined and customized options in various categories – HVAC, envelope components, appliances, schedule, and so on - to specify options to be considered in building energy modeling. Energy performance of homes are calculated relative to a reference. The reference can be either a user-defined reference, a climate-specific Building America Benchmark for new construction, or an "Existing (w/ Min Replace)" reference for retrofit. The team used the "Existing (w/ Min Replace)" option for this project, which incorporated the known pre-existing building characteristics, appliances, occupant schedules, etc. The retrofit version was defined as the "My Design" model in BEopt and this model included the upgrades to the building envelope and the new, low-capacity HVAC system.

Model Calibration

The team created and calibrated BEopt models for the individual sites to match, to the extent possible, the raw utility data on gas and electricity consumption. The models used historical weather data obtained from nearby weather stations, which are listed in Table 11.

The team obtained critical input parameters related to the building envelope, HVAC, heating and cooling set points, major appliances, and other building characteristics from site audits, feedback and survey responses from the homeowners, as well as site monitored data for the prior and low-capacity HVAC periods. Assumptions were made

[3] https://beopt.nrel.gov/home

about the required input parameters when the exact information was not directly available; these assumptions utilized standard input parameters available within BEopt.

Estimation of Energy Savings

Once calibrated, the team used the models with typical meteorological year (TMY) weather data from the nearby weather stations for comparing the energy performance of the homes during the prior and low-capacity HVAC periods. For the TMY simulations, standard heating and cooling set point- of 68° Fahrenheit (F) and 78°F were assumed for all sites and all periods. The other input parameters were the same as the models used for calibration. The TMY models results of HVAC energy use were compared for the pre- and post-retrofit cases.

Site Testing, Data Monitoring and Analysis

The team has been collecting site monitoring data since August 2019, shortly after installation of the new furnace, AC and the envelope upgrades. The objective of this monitoring was to help explain the findings of the preceding energy savings analysis, provide information to use in the calibration of the simulation, and to understand the operation of the new system. It is important to note, however, that no site data was collected from the prior system, so no direct HVAC performance comparison can be made with the prior system. The experimental design enabled comparison between the operation at high (HI) and low (LO) fire stages of the low-capacity HVAC system.

One-time Field Tests

The team performed the following tests at the test sites to support the site monitoring and analysis.

Heating and Cooling Rates

The team acquired measurements of supply and return temperatures, relative humidity and air flow in heating and cooling modes to estimate the energy delivery rate.

Temperature Stratification

To test the hypothesis that low-capacity systems with longer run times and appropriate volumes of delivered air should deliver superior air mixing, the team measured temperature stratification in the homes following installation of the low-capacity HVAC system. It is noted that all homes were single story buildings. Measurements were taken using an infrared "gun" after the system had been running at full cooling or heating for up to an hour. The team took readings at floor level, that is 6-12" from floor, mid-level or thermostat height, ~60" from floor, and at ceiling level, that is 6-12" from ceiling.

Monitored Data and HVAC Performance

The project team monitored the key parameters related to the HVAC performance and comfort conditions at all sites. The data was collected at 15 second intervals for energy measurements and 5-minute intervals for temperature and relative humidity (RH). Table 12 provides the complete list of the measured parameters and sensors.

Table 12: List of Measured Parameters, Sensors, and Locations

Point No.	Measurement Name	Location	Sensor Type	Units
1	Air Conditioner Power	Outdoor Unit	Power Meter	W
2	Furnace Gas Use	Furnace/air handler unit (AHU)	Gas Meter	ft^3
3	Furnace Power	Furnace/AHU	Power Meter	W
4	Outside RH	Ecobee Thermostat	Humidity	%RH
5	Outside Temperature	Ecobee Thermostat	Temperature	°F
6	Cooling Setpoint	Ecobee Thermostat	Temperature	°F
7	Heating Setpoint	Ecobee Thermostat	Temperature	°F
8	Indoor RH	Ecobee Thermostat	Humidity	%RH
9	System mode	Ecobee Thermostat	Control	Status
10	Indoor Temperature – Primary Zone	Ecobee Thermostat in common area	Temperature	°F
11	Indoor Temperature – Secondary Zone	Ecobee Remote Sensing Unit in bedroom	Temperature	°F

Source: Frontier Energy

Comfort Conditions

To ascertain the comfort conditions within the test homes, the team measured space temperatures and relative humidity (RH). The measurements were plotted against ASHRAE comfort zone plot to gauge whether the monitored conditions would be considered comfortable.

Cycling and Runtime

Runtimes were expected to be higher for a lower capacity system. The team inferred runtimes for the system in cooling or heating mode by analyzing both the gas and electric consumption and the system mode, as recorded by the Ecobee thermostats. These thermostats reported the number of seconds that the system was calling for cooling or heating during every five-minute period. The five-minute totals could be summed across an hour, day, or month to calculate runtime.

The team expected that system cycling would also be affected by the capacity setting of the system. Cycles were determined by analyzing 15-second gas or outdoor-unit electricity consumption and detecting how many times per day the system transitions from OFF, that is zero energy consumption for at least a minute, to ON or a non-zero reading.

Delivered Energy, Energy Consumption and Efficiency

The team estimated the rate of energy delivered using one-time measurements of supply and return air temperatures, RH, and unit airflow rates with the unit in full cooling and full heating modes. The rate of energy delivered was calculated using the following equation:

$$\textit{Rate of Energy Delivery} = 1.08 \times CFM \times |(T_{SUP} - T_{RET})| \tag{2}$$

where the rate of energy delivery is in Btu/hour, 1.08 is a combination of heat capacity and density of air, CFM is the airflow rate in cubic feet per minute, and T_{SUP} and T_{RET} are the dry-bulb temperatures of the outgoing and incoming air, respectively, in °F.

The team measured the gas consumption of the furnace using an in-line pulse-generating gas meter and the electricity consumption of the indoor fan and outdoor condensing unit using watt-hour transducers with current transformers. Data was collected at 15-second intervals and aggregated to hourly, daily, and monthly periods.

Efficiency was calculated as kBtu of useful energy delivered for cooling or heating divided by kBtu of energy consumed, electricity or gas or both.

Human Factors and Survey Questionnaires

One objective of this study was to explore if installing a lower-capacity furnace impacts the comfort provided. The project team conducted multiple surveys asking about how the system was operated, the occupants' objectives, and their impressions of the system. Similar questionnaires were delivered multiple times to get information on the different systems and operating modes of both the prior systems and the low-capacity HVAC system.

- Summer 2018 / Winter 2018-19: Prior system Heating and Cooling
- Summer 2019 / Winter 2019-20: Prior Cooling and low-capacity system, LO fire stage Heating
- Summer 2020: Low-capacity system, LO fire stage Cooling
- Winter 2020-21: Low-capacity system, HI fire stage Heating
- Summer 2021: Low-capacity system, HI fire stage Cooling

Temperature Dynamics Test

The project team also conducted a test of the temperature dynamics of the homes, to aide in understanding how well the homes can recover from temperature setbacks and pre-cooling. The results of this test were more indicative of the response of the insulation and thermal mass of the building itself than the air conditioning system. A well-insulated home is expected to maintain comfort conditions longer without having to run the air conditioner. In each home, the team manipulated the temperature setpoint remotely and the resulting indoor air temperatures were recorded. The following procedure was used:

- Start in cooling mode and set cooling setpoint to 52°F.
- Wait until space temperature reaches 52°F or an hour has passed, whichever is sooner.
- Change to heating mode and set heating setpoint to 92°F.

- Wait until space temperature reaches 92°F or an hour has passed, whichever is sooner.
- Change to cooling mode and set cooling setpoint to 72°F.
- Wait until space temperature reaches 72°F.
- Revert to running normal thermostat program.

Pre-Cooling Feasibility

Finally, the team conducted experiments at two test homes to evaluate how well the retrofit measures and the low-capacity HVAC system perform when a home is pre-cooled. Pre-cooling means that the home is cooled to a lower than usual temperature during the hours just preceding the typical utility peak period, and then minimizing or eliminating the use of air-conditioning during the peak period, while hopefully maintaining the home temperature at acceptable comfort levels.

The hypothesis is that the peak period would start with cooler than usual interior conditions and the retrofit measures would reduce the heat gains during the peak period to prevent the interior temperature from reaching the higher cooling set point. While this may come at the cost of minimal increases in daily energy use, ideally there will be no energy consumed for air conditioning during the peak period or the energy consumption will be reduced.

One concern that people may have about a lower-capacity system is that if a homeowner were to implement a simple daytime set-back during the summer, that is increasing the cooling setpoint by a few degrees when the home is unoccupied, and return home after work to a very hot house, greater than 83°F, they may be unable to recover to a comfortable temperature in a reasonable amount of time. Precooling can obviate the need for oversizing equipment to provide this kind of rapid and substantial temperature reduction.

In this limited test, the project team controlled each home's temperature setpoints for a week. The thermostat setpoint schedules imposed were:

- A low temperature from 12 PM to 4 PM—varied each day, in the range 72-76°F.
- 80°F (or higher) from 4 PM to 9 PM.
- Any "comfortable" temperature from 9 PM to 12 PM on the following day.

The team advised homeowners about alternate ways to achieve comfort should the home overheat, including turning on ceiling or desk fans or opening windows if outside conditions are favorable, while explicitly being allowed to turn on the AC temporarily at any time during the peak period if needed to achieve comfort. Throughout this week the team asked occupants questions by email:

- Were you uncomfortably cool from noon to 4 PM? How acceptable was it?
- Were you uncomfortably warm from 4 PM to 9 PM? At about what time did you start to feel uncomfortable? How acceptable was it?
- What things did you try to cope with the heat from 4 PM to 9 PM?

- If you did turn on the AC from 4 PM to 9 PM by temporarily lowering the setpoint, can you describe reason(s) to turn it on?
- If you did turn on the AC from 4 PM to 9 PM by temporarily lowering the setpoint, about how long was it before conditions were acceptable again?
- What happened at 9 PM? Did you turn on the AC or open windows? About how long was it before conditions were acceptable again?

The team monitored temperature setpoints from schedule and temporary overrides, interior and exterior temperatures, and AC operation as usual throughout the week. The monitoring during the pre-cooling test period is just a continuation of the already implemented monitoring.

Stakeholder Feedback

At the end of the project, the project team interviewed several stakeholders to identify what they felt were the most interesting findings and implications from this research. An interview guide was used, including the following questions:

- Describe, in your own words, what was done in the project.
- What were the BEST things about this technology implementation?
- What were the WORST things about this technology implementation?
- What do you perceive to be the biggest benefits of using lower-capacity systems?
- What do you anticipate are the biggest barriers to taking best advantage of lower-capacity systems?
- Based on what you’ve seen, would you recommend that lower-capacity HVAC systems be further promoted in the industry?
- If you’re not convinced, what more would you want to see to convince you that these measures provided value? Or what would need to be changed about the measures to make it worth recommending?
- What do you see as the potential for these measures in the future? Could these measures be pushed to be even more impactful?
- Ultimately, how should these measures be promoted?

CHAPTER 3: Project Results

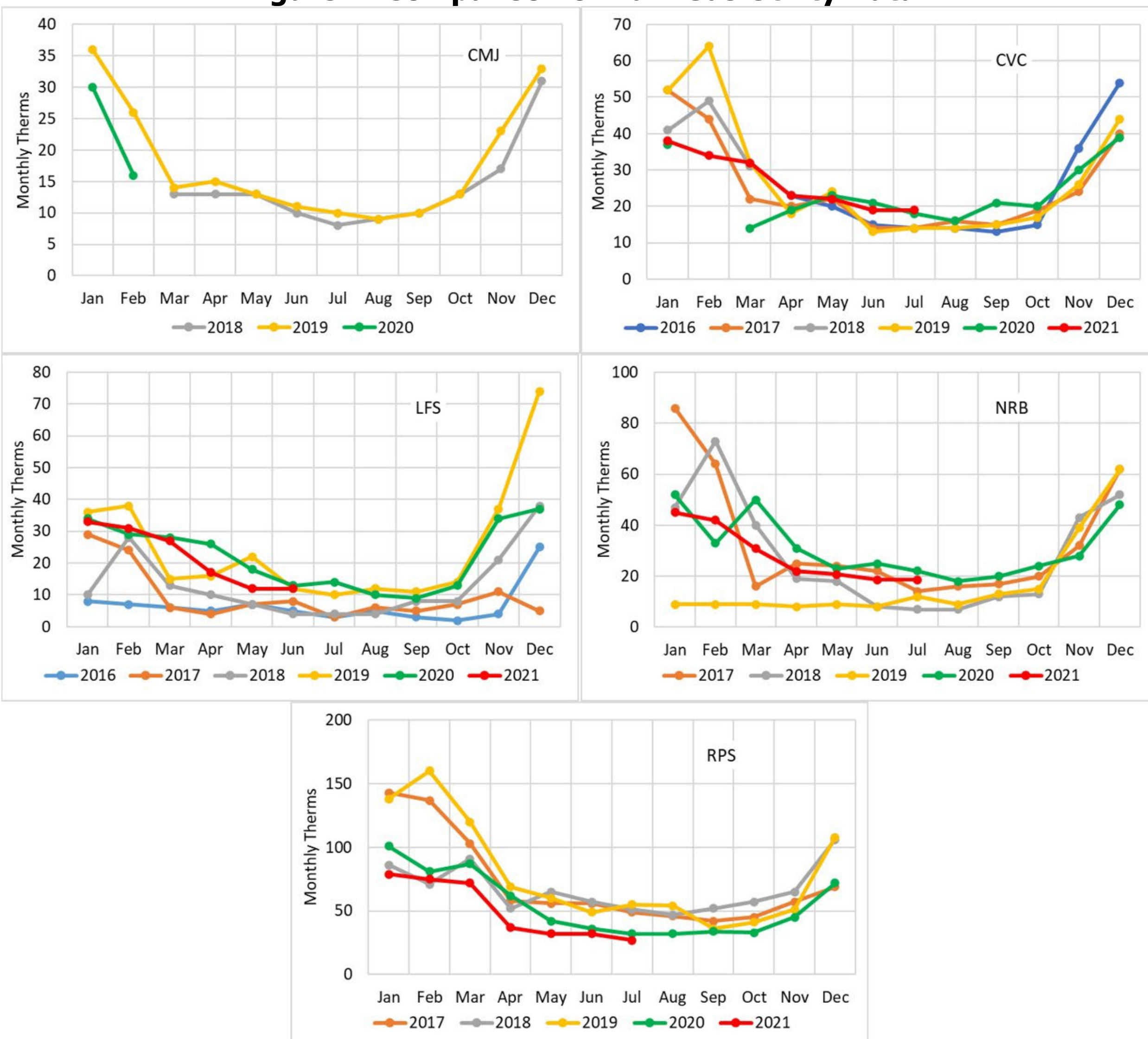
Utility Data

The following sections present the utility data from the different sites and the analysis results.

Raw Data Comparison

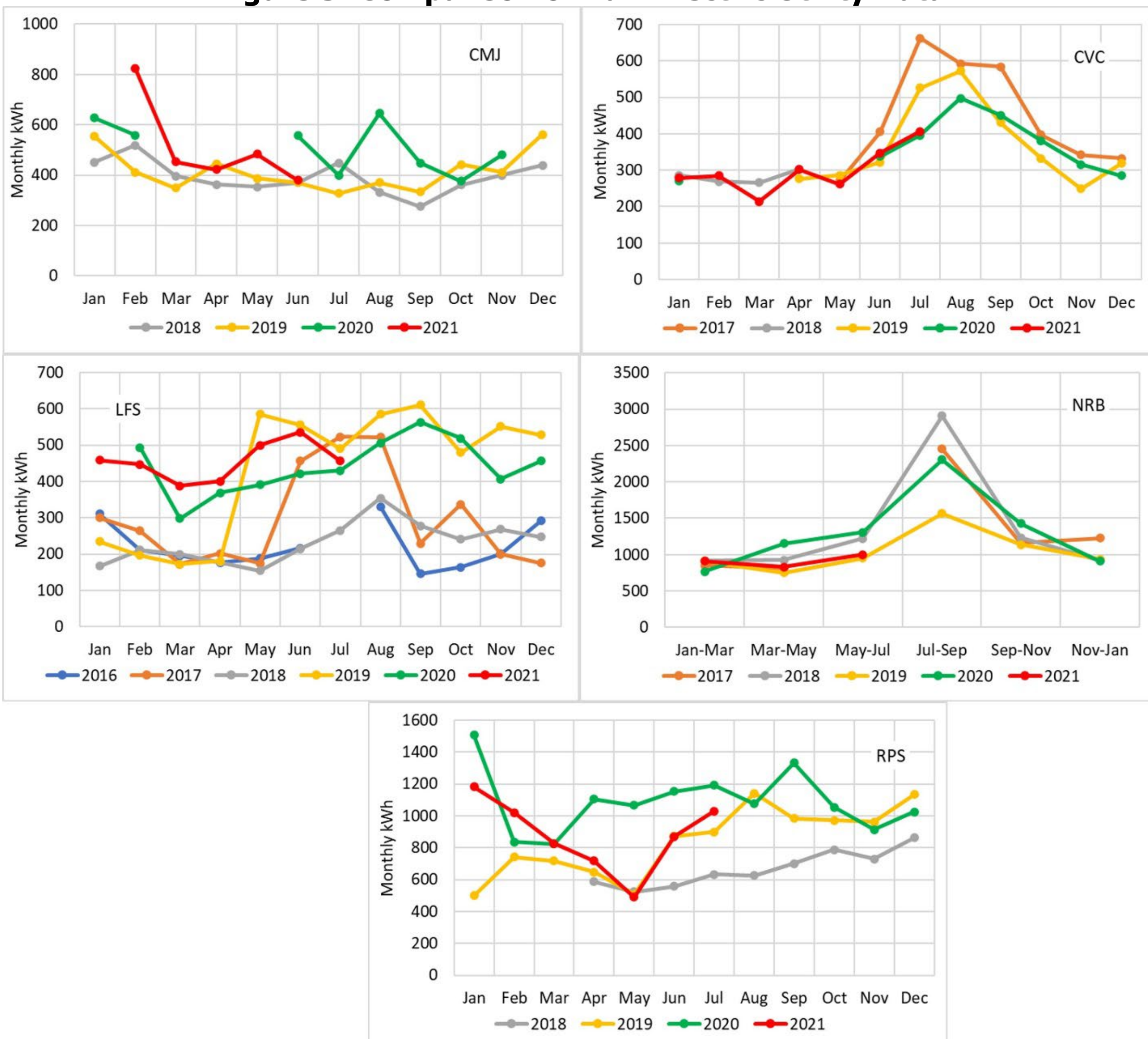
Figure 2 and Figure 3 compare the raw monthly therms from the utility bills from the different sites through mid-2021. The gas use patterns showed some variability across different years, but in general followed the expected trend of high consumption in winter and low consumption in summer. The electricity use patterns showed significant variations across different years at CMJ, LFS and RPS, with no discernible seasonal trends. Seasonal trends of higher electricity consumption during summer and lower consumption during winter were observed at CVC and NRB.

Figure 2: Comparison of Raw Gas Utility Data



Source: Gas Technology Institute

Figure 3: Comparison of Raw Electric Utility Data



Source: Gas Technology Institute

The first half of 2019 and the previous years are before the low-capacity systems were installed. The second half of 2019 and most of 2020 represent the LO fire stage period of the low-capacity HVAC for all sites except CMJ. During this period, the contractor inadvertently set the low-capacity system at CMJ to modulating operation mode, that is it could switch between the high and low fire stages based on demand. The contractors switched the low-capacity systems to the HI fire stage at NRB during August 2020 and at CVC, LFS and RPS during December 2020. At CMJ, the low-capacity system was switched from the modulating mode to the LO fire stage during December 2020.

Utility data was available for different time periods from the different sites and are shown here primarily for the purpose of illustration. No direct conclusions were drawn from the raw utility data shown, which are dependent on weather as well as occupant behavior.

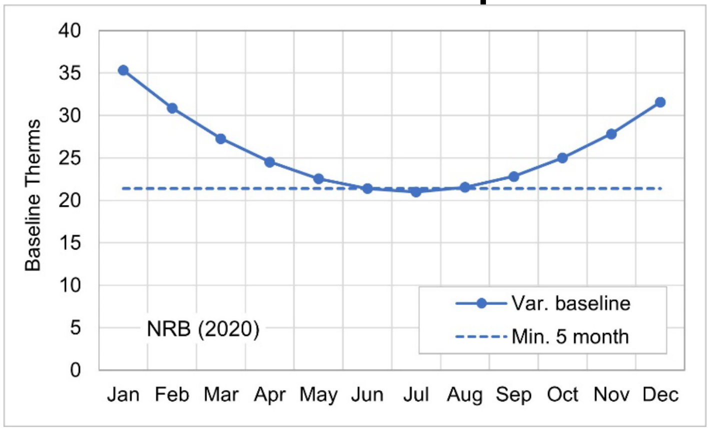
At some sites, similar consumption profiles were observed across the different years – for example, the CMJ and CVC sites. In other cases, the monthly energy usage varied appreciably from year-to-year and within the same year as well. Some unusual or anomalous consumption periods were observed, and the project team sought feedback from the homeowners to better understand the utility data. Following is a summary of the feedback from the homeowners:

1. The ownership of the CVC test home changed during March-April 2020 and the new occupants moved into the home on April 25, 2020. Therefore, it is likely that the home was unoccupied between March and April.
2. Very low gas consumption was observed at NRB during January-May 2019. Based on homeowner feedback, during this time, their furnace was not working, and they used a space heater instead.
3. Electricity usage at LFS varied from low consumption during summer 2018 to much higher consumption during summer 2019. According to the homeowner, the HVAC system was not working at certain time periods. The occupancy increased from one to two during 2019 and an electric vehicle charger was also installed in mid-2019.
4. At RPS, the electricity usage consistently increased during 2019. A major load was the pool pump with the filtration system needing to be run for longer periods, till about April 2020 when the filter was replaced. Each year post-December, the homeowners intermittently used electric heaters with increased occupancy during the winter college break. It is further noted that, prior to the low-capacity system replacement in 2019, this home did not have an air conditioner, hence the low electricity consumption during the summer of 2018.

Baseline vs. HVAC Energy Estimates

To estimate the HVAC energy consumption, the team calculated the baseline gas and electricity consumption as described in Chapter 2. It was assumed that water heating was responsible for 67 percent of the baseline gas consumption and the remaining 33 percent was attributed to other appliances like clothes dryer, cooking range, and so on. The variable gas consumption for water heating was calculated using the monthly WHM. Next, the overall monthly gas baseline was calculated using equation (1). As an example, Figure 4 shows the baseline gas consumption calculated for NRB during 2020.

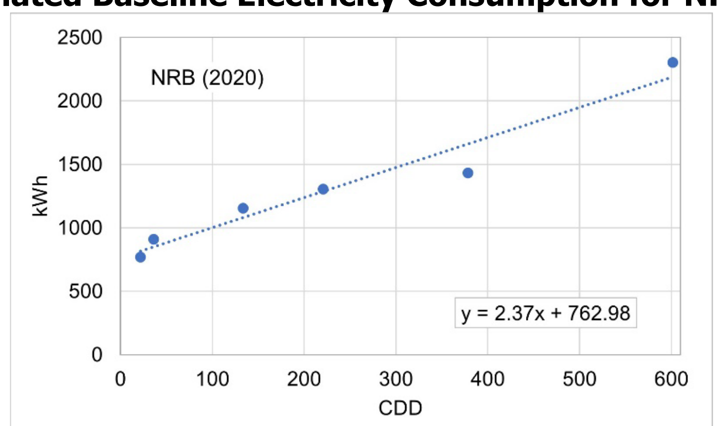
Figure 4: Calculated Baseline Gas Consumption for NRB During 2020



Source: Gas Technology Institute

For the baseline electricity consumption, the monthly kWh values were plotted against the calculated cooling degree days (CDD) and extrapolated to CDD = 0 to estimate the baseline consumption; the assumption being that at zero CDD, no cooling is needed. Figure 5 shows the calculation of baseline electricity consumption of 763 kWh for NRB in 2020 as an example. For LFS, no clear correlation was observed between monthly kWh values and CDD, so the average of the lowest five months of consumption during each year was used.

Figure 5: Calculated Baseline Electricity Consumption for NRB During 2020



Source: Gas Technology Institute

Degree Day Normalization and HVAC Energy Savings

The team used HDD and CDD values to normalize the estimated HVAC energy to account for the variable weather conditions during different years. The HDD and CDD values were calculated as follows:

$$HDD = \sum T_{Base,H} - T_{out}\,, if\ T_{Base,H} > T_{out} \quad (3)$$

$$CDD = \sum T_{out} - T_{Base,C}\,, if\ T_{Base,C} < T_{out} \quad (4)$$

In the above equations, T_{out} is the outdoor temperature from the nearby weather stations. $T_{Base,H}$ and $T_{Base,C}$ are the base heating and cooling temperatures obtained from regression analysis of the site monitored heating and cooling energy consumption vs. T_{out}. Table 13 lists the base HDD and CDD temperatures for the different sites. Cumulative HDD and CDD values were calculated over the respective monthly or aggregate summer and winter periods. Appendix A provides further information on HDD and CDD calculations.

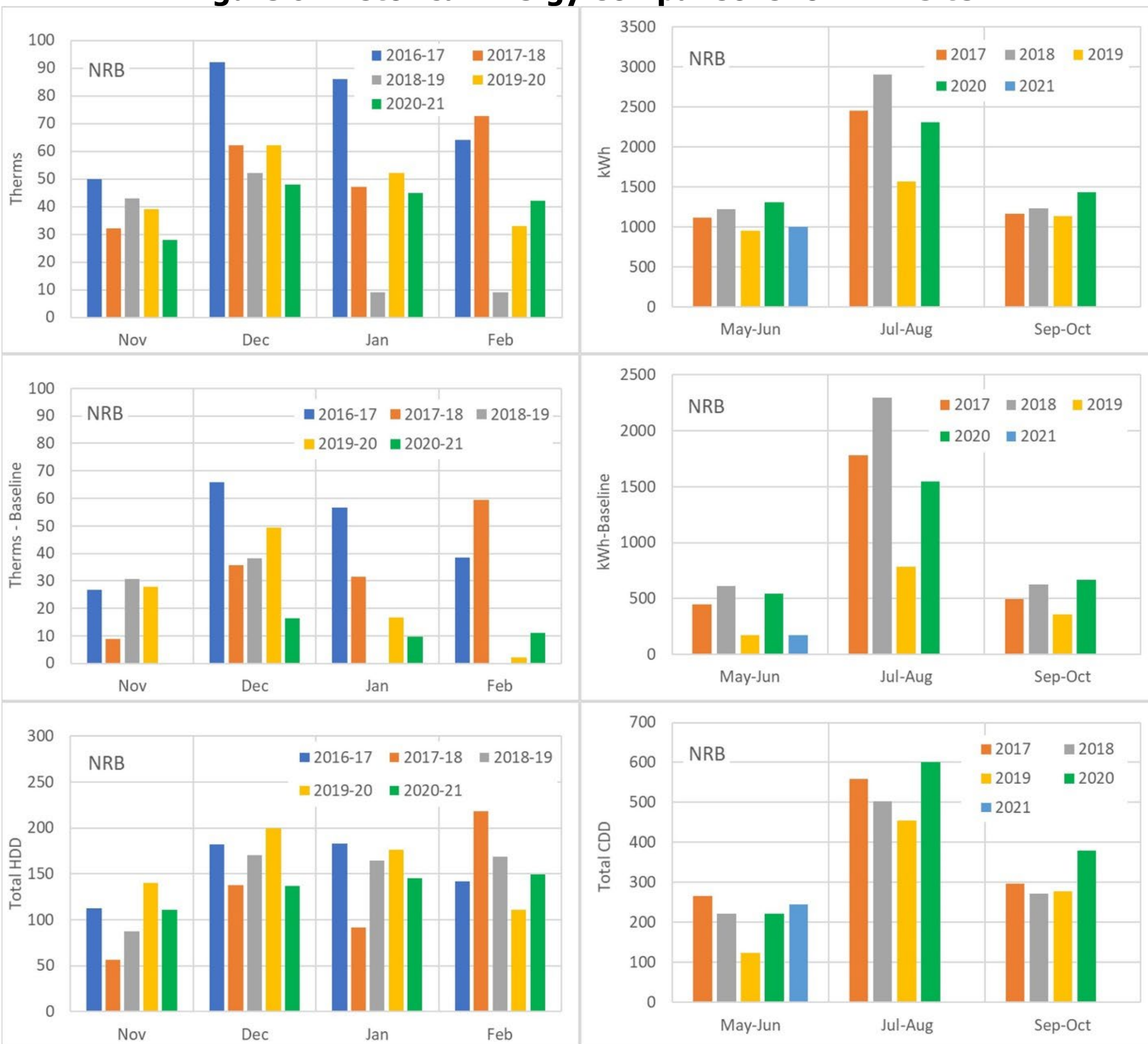
Table 13: Weather Stations

Site	CMJ	CVC	LFS	NRB	RPS
Weather station (WMO #)	Santa-Ana-John-Wayne-AP (722977)	Brackett (722887)	Santa-Ana-John-Wayne-AP (722977)	Van-Nuys-AP (722886)	Torrance-Muni-AP (722955)
HDD base T (°F)	62.2	69.6	61.4	60.1	60.1
CDD base T (°F)	68.2	64.9	65.3	71.9	65.0

Source: Frontier Energy

To illustrate how HDD and CDD might impact energy consumption, Figure 6 shows an example compilation of energy consumption - total and heating/cooling-only - and total CDD and HDD during the summer and winter months for the NRB site. The winter periods were assumed to consist of November-February of subsequent years and the summer periods were assumed to comprise of June-September. In the case of NRB, the electricity bills were typically consolidated over multiple months. Both raw and HVAC-only energy consumptions varied across the different years.

Figure 6: Historical Energy Comparisons for NRB Site

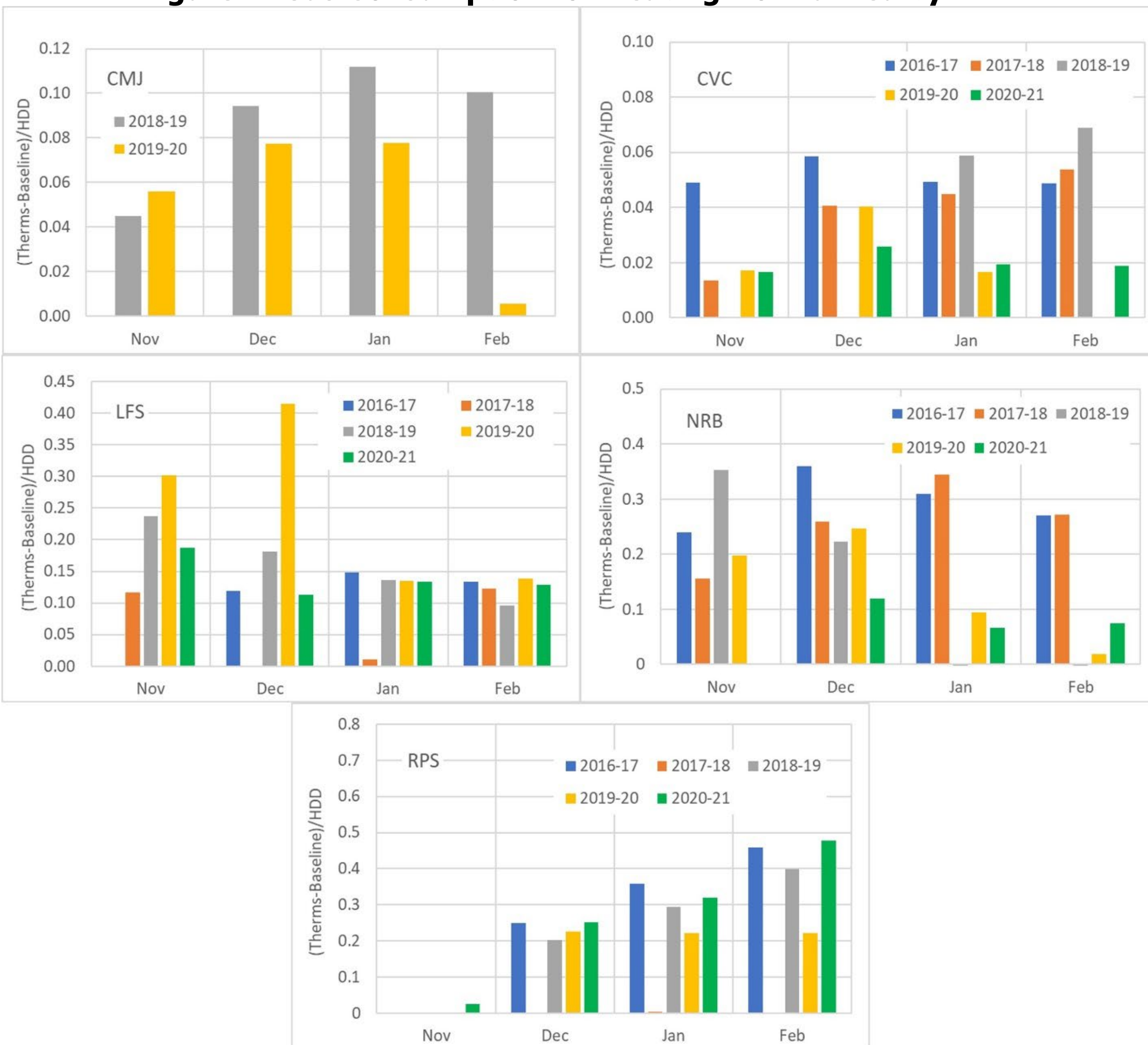


Top row – raw Therm and kWh consumption; Middle row – Therm and kWh consumption for HVAC only, that is without the baseline consumption; Bottom row – total HDD and CDD values during the corresponding periods.

Source: Gas Technology Institute

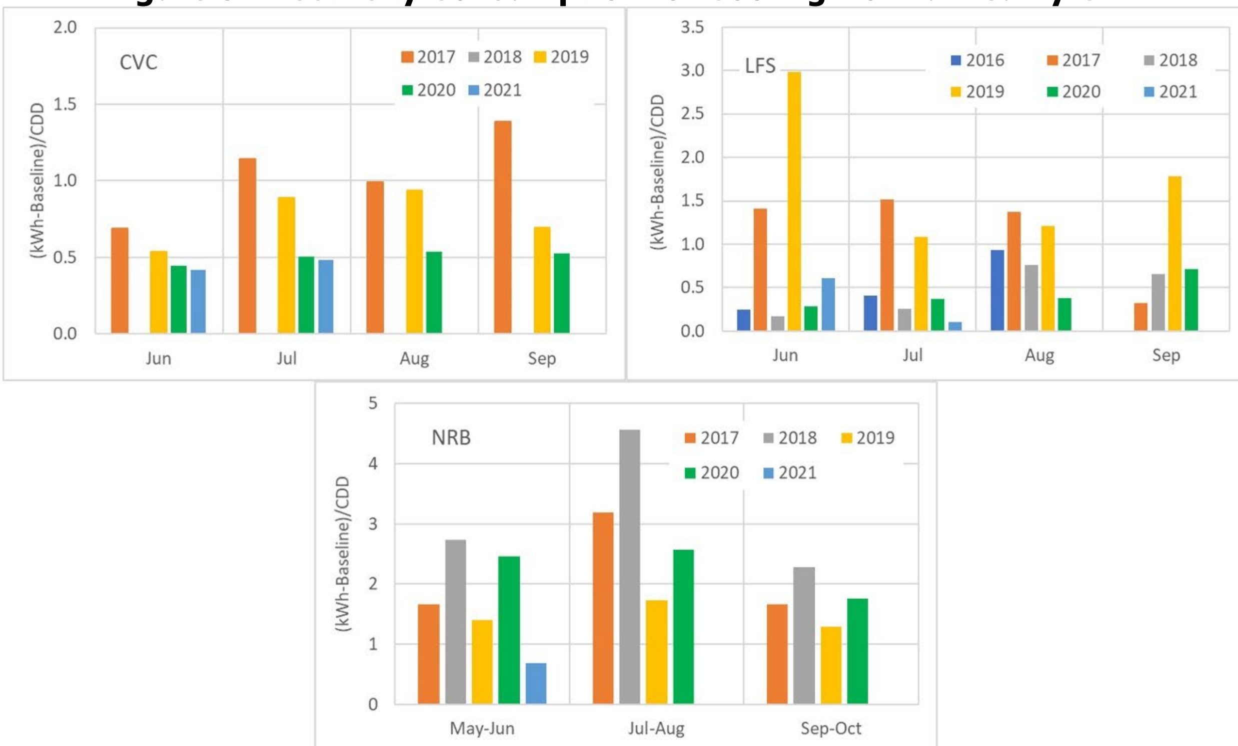
Next, the team normalized the estimated heating and cooling energy consumption without the baseline gas and electricity use by the monthly total HDD and CDD values over the corresponding billing periods. Figure 7 and Figure 8 show the results for all sites. The team did not perform CDD normalization of the electricity consumption at the CMJ and RPS sites because those sites did not have an AC prior to the HVAC replacement and even after the replacement there was little to no cooling energy consumption.

Figure 7: Gas Consumption for Heating Normalized by HDD



Source: Gas Technology Institute

Figure 8: Electricity Consumption for Cooling Normalized by CDD

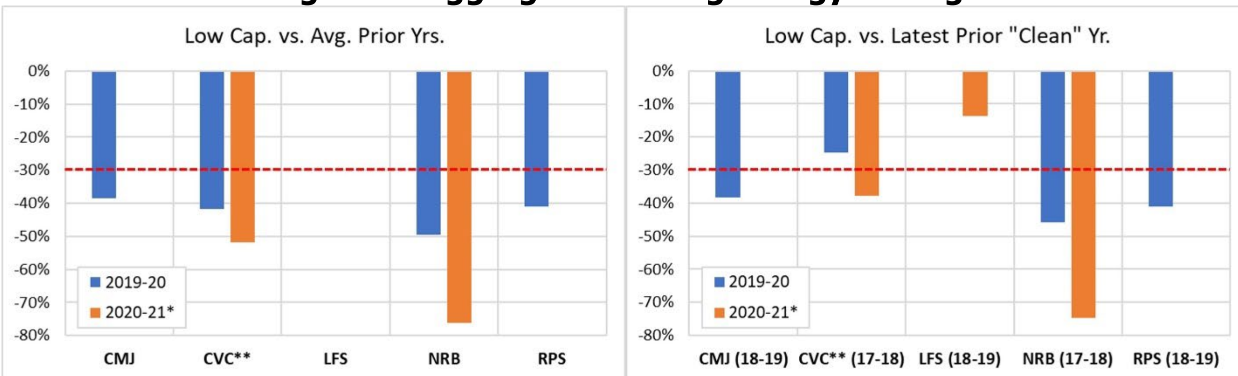


Source: Gas Technology Institute

To check for energy savings based on utility data, the team calculated the aggregate energy consumption for heating and cooling during the winter and summer months, respectively, for the different years. The savings were calculated based on estimated gas consumption for heating, that is raw utility gas data less baseload, normalized by the respective HDD. The savings were calculated against two baselines – first, the average of the heating energy use from the winter periods before the low-capacity HVAC installation when the data was available, that is 2018-19 and earlier, and second, the previous "clean" winter period, when there were no known anomalies in the gas consumption. For example, the heating system at NRB was not working during winter 2018-19, hence the winter of 2017-18 was used as the "clean" baseline for NRB.

Figure 9 shows the estimated heating savings for the 2019-20 and 2020-21 winter periods. The gas consumption during the 2020-21 winter period included both the low and high fire stages of the low-capacity system at CVC, LFS and RPS, as the switchover happened during December 2020 at these sites. At NRB, the 2020-21 winter period only included the low-capacity system operation at the high fire stage as the switchover was done in August 2020. At CMJ, the 2020-21 period included modulating and low fire stage operations. In one case, the 2017-18 winter period for RPS, the estimated variable baseline Therms were calculated to be greater than the actual Therm consumption, resulting in a negative value of the aggregate Therms. Thus, RPS 2017-18 winter period was excluded from this analysis.

Figure 9: Aggregate Heating Energy Savings



Left – compared to all previous years; Right – compared to the latest previous "clean" years, which are denoted in the x-axis labels

Source: Gas Technology Institute

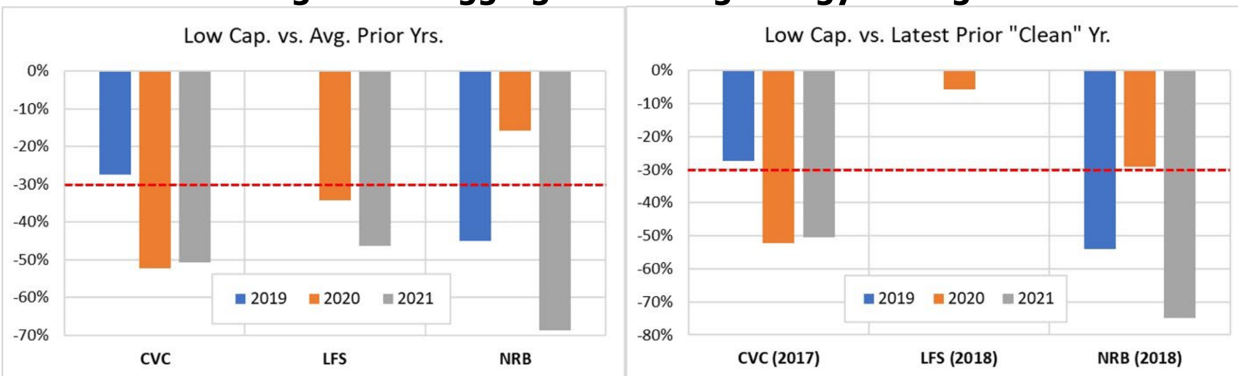
The dashed red lines in Figure 9 represent the target 30 percent savings and in most cases, the calculated savings exceeded the target value. Data from CMJ for the 2020-21 period was not available. The other missing bars for LFS and RPS in Figure 9 indicate that the normalized aggregate heating energy use was higher during 2019-20 and 2020-21 than the previous years. In case of RPS, the actual gas consumption during 2020-21 was lower than previous years, but after baseline correction and HDD normalization, the value was higher than previous years.

A simple average of the savings from all sites was 12 percent compared to all prior years and 22 percent compared to previous "clean" year. At LFS, the aggregate values were observed to increase compared to previous winters; the exact reasons are not known, but the increase in occupancy during 2019 can partially explain the increased energy use. Excluding LFS, the simple averages of the savings were 38 percent and 33 percent compared to all prior years and latest "clean" prior year, respectively.

Figure 10 shows the estimated aggregate cooling energy savings for CVC, LFS and NRB. CMJ and RPS did not have air conditioning prior to the low-capacity system installation and, hence, no cooling savings analysis was performed for those sites. The missing 2019 and 2021 bars for LFS indicates an increase in normalized cooling energy consumption compared to previous years. Only partial summer kWh data was available for summer 2021. Therefore, to analyze and compare the 2021 summer performance, only June and July kWh data were used for prior years and 2021.

Again, the estimated savings exceeded the 30 percent target in most cases. The simple average savings across all sites were 43 percent compared to all prior years and 28 percent compared to the latest "clean" prior year. Excluding LFS, the simple average savings were 43 percent and 48 percent.

Figure 10: Aggregate Cooling Energy Savings



Left – compared to all previous years; Right – compared to the latest previous "clean" years, which are denoted in the x-axis labels

Source: Gas Technology Institute

It should be noted that raw utility data and heating or cooling energy consumption normalized by HDD or CDD showed substantial variance across different years. While HDD and CDD normalization can eliminate the impact of weather to an extent, it does not capture the impact of occupant behavior on energy consumption. The variance in the normalized data indicates differences in occupancy and behavior patterns impacting the energy consumption, in addition to the impact of weather.

Building Energy Modeling

The team performed building energy modeling using BEopt to support the utility data analysis. As noted earlier, models of all test homes were tuned and calibrated against the utility data. Following calibration, these models were used to estimate the specific HVAC savings under a common set of occupancy and weather conditions.

Model Calibration Results

Table 14 summarizes the major appliances and energy consumers that were assumed for the homes and whether they ran on gas (G) or electricity (E). Summaries of the known and assumed building characteristics for each site are listed in Table 14.

Table 14: List of Major Appliances

Appliance	CMJ	CVC	LFS	NRB	RPS
Water heater	✔ (G)	✔ (G)	✔ (G)	✔ (G)	✔ (G)
Refrigerator	✔ (E)	✔ (E)	✔ (E)	✔ (E)	✔ (E)
Extra refrigerator				✔ (E)	
Cooking range	✔ (E)	✔ (G)	✔ (G)	✔ (G)	✔ (G)
Dishwasher	✔ (E)	✔ (E)	✔ (E)	✔ (E)	✔ (E)
Clothes Washer	✔ (E)	✔ (E)	✔ (E)	✔ (E)	✔ (E)
Clothes Dryer	✔ (E)	✔ (G)	✔ (G)	✔ (G)	✔ (G)
Pool Heater					✔ (G)
Pool Pump					✔ (E)
Hot Tub/Spa Pump			✔ (E)		

Source: Gas Technology Institute

Site CMJ

Table 15 summarizes the building characteristics reported in the "Home Performance Upgrade Report", which were incorporated in the BEopt models. The parameters are listed for the pre-retrofit or "prior" period and the post-retrofit period following the HVAC replacement and other retrofit measures. Based on site-monitored data, the AC was not being used even after the HVAC replacement. In BEopt, an artificially high cooling set point was used to preclude any cooling energy consumption during the post-retrofit period even though an AC was installed.

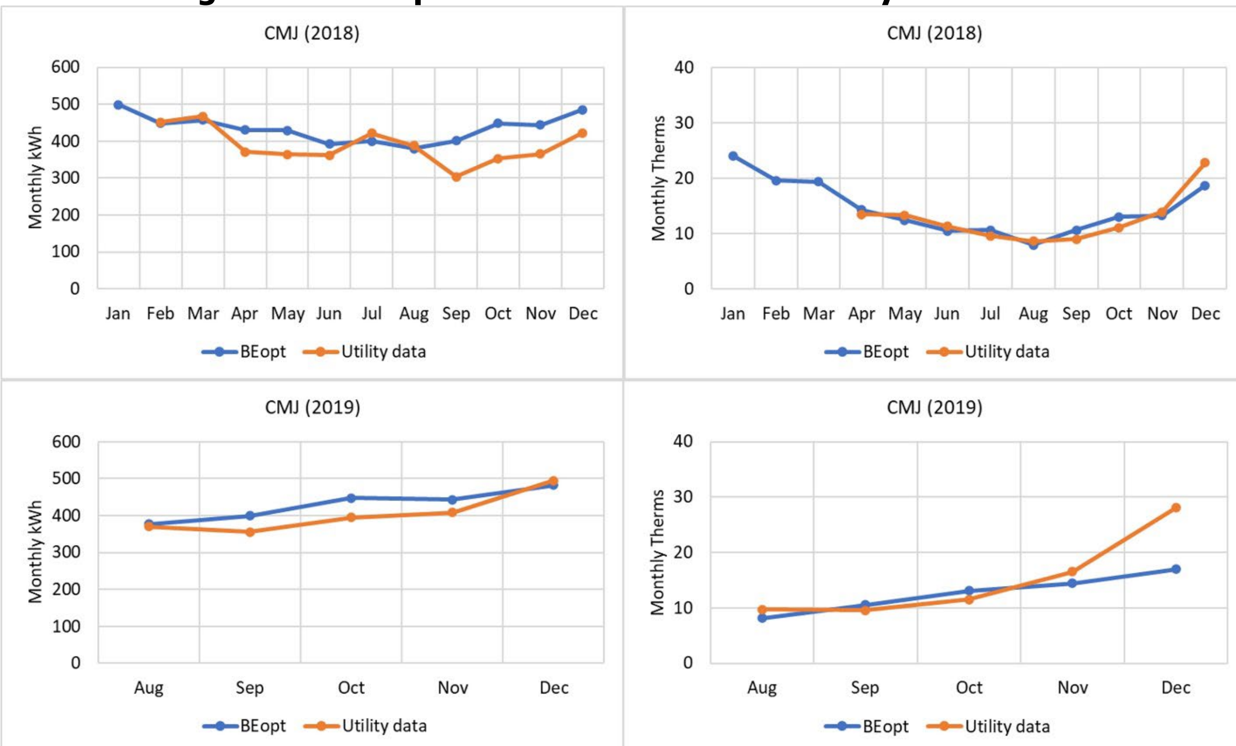
Table 14: Building Characteristics - CMJ

	Prior	Post-retrofit
Furnace	75 kBtu/h, 80% AFUE	26 kBtu/h, 96.15% AFUE
AC	No AC	1.5 tons, 16 SEER
Wall Insulation	R-13 Blown Cellulose	R-13 Blown Cellulose
Foundation Insulation	None	None
Roof/Attic Insulation	R-30 Cellulose degraded to R-19	R-38 Cellulose
Air Leakage (ACH50)	8.5	8.5
Duct Location, Insulation	Attic, R-4.2	Attic, R8 buried ducts
Duct Leakage	0% leakage to outside	0% leakage to outside
Cooling set point	Not applicable	No AC use
Heating set point	69.8°F	69.8°F

Source: Gas Technology Institute

Figure 11 shows the comparison of the modeled results and utility data. The utility data periods were not coincident with the respective months. Therefore, the energy use per day was calculated from the utility data and applied to the respective monthly periods for comparison with the modeled results. The comparison is shown for the pre-retrofit 2018 period and the second half of 2019, which is part of the post-retrofit period. The post-retrofit period is assumed to span August-December 2019. The models were able to capture the energy consumption trends and the modeled results showed reasonable agreement with the utility data. It should be noted that for the post-retrofit period, the model assumed the low-capacity system to be operating in the low fire stage. Even though the system was set to modulating operation, the site monitored data showed that the low-capacity system operated in the low fire stage for 80 percent of the time.

Figure 11: Comparison of Modeled and Utility Data - CMJ



Source: Gas Technology Institute

Site CVC

Table 16 lists the CVC building characteristics and some of the model assumptions. Figure 12 shows the comparison of the modeled results with the utility data for the pre-retrofit 2017 and post-retrofit 2020 periods.

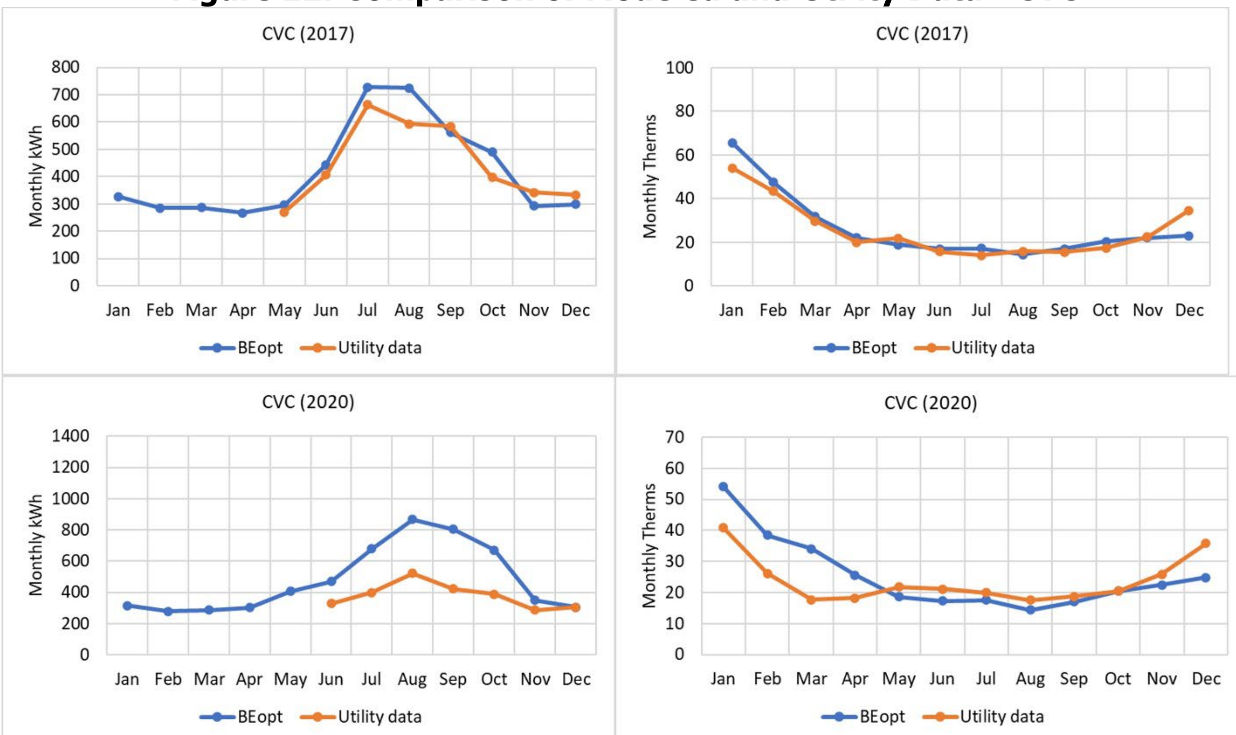
Table 15: Building Characteristics - CVC

	Prior	Post-retrofit
Furnace	75 kBtu/h, 81% AFUE	26 kBtu/h, 96.15% AFUE
AC	4 tons, 12 SEER	1.5 tons, 16 SEER
Wall Insulation	R-11	R-11
Foundation Insulation	None	None
Roof/Attic Insulation	Vented Attic, R-30	R38
Air Leakage (ACH50)	7.5	7.5
Duct Location, Insulation	Attic, R-4	Attic, R8 buried ducts
Duct Leakage	59 CFM25 to outside	59 CFM25 to outside
Cooling set point	74°F (9 AM – 9 PM); 78°F (9 PM – 9 AM)	77°F

Heating set point	70°F	69°F

Source: Gas Technology Institute

Figure 12: Comparison of Modeled and Utility Data - CVC



Source: Gas Technology Institute

Site LFS

Table 17 lists the LFS building characteristics. In the LFS home, the leaky duct system and enclosure were addressed by air sealing at the attic plane, replacing the attic ducts and adding more attic insulation to bury the ducts. However, the new leakage rates could not be tested due to concerns over residual asbestos in the duct system, so the same air leakage rate was assumed for the post-retrofit period.

Table 16: Building Characteristics - LFS

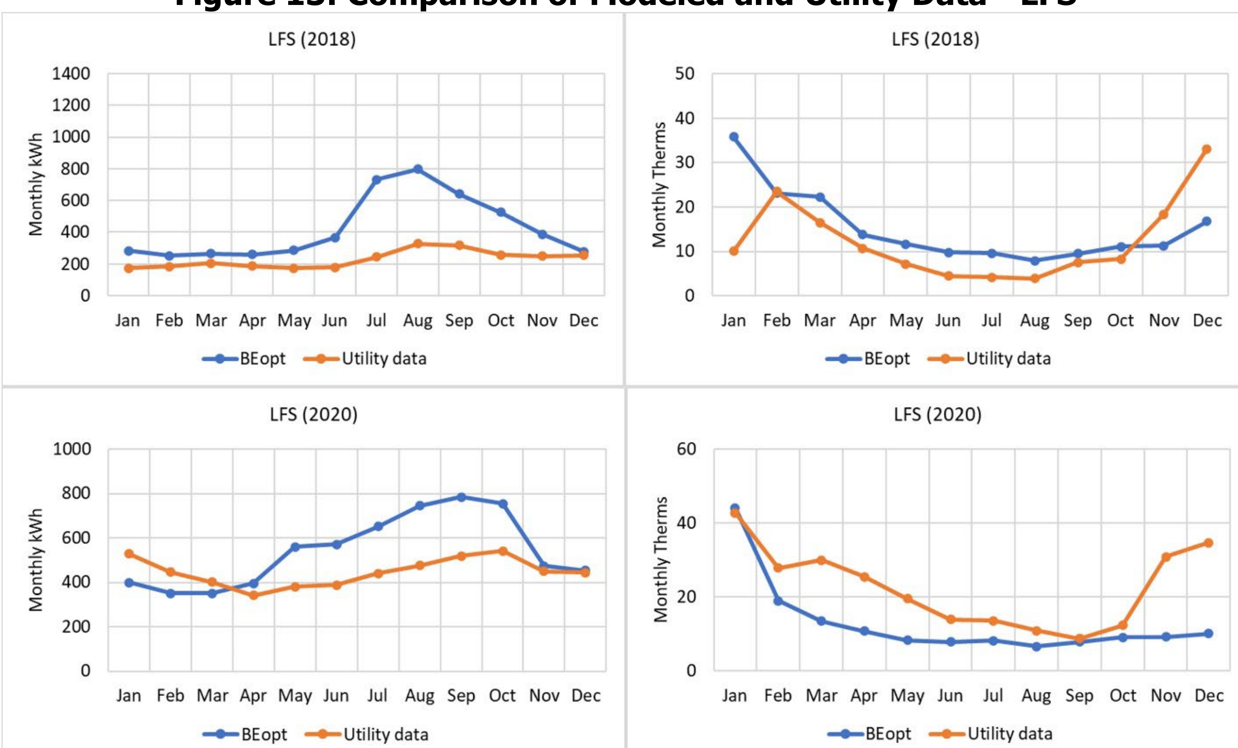
	Prior	**Post-retrofit**
Furnace	80 kBtu/h, 95.5% AFUE	26 kBtu/h, 96.15% AFUE
AC	3 tons, 16 SEER	1.5 tons, 16 SEER
Wall Insulation	R-11	R-11
Foundation Insulation	None	None
Roof/Attic Insulation	R-11 Grade 3 (R-4 equivalent)	R38
Air Leakage (ACH50)	13	Not tested; 13 assumed

Duct Location, Insulation	Attic, R2.1	Attic, R8 buried ducts
Duct Leakage	422 CFM to outside	Not tested; 15% assumed conservatively
Cooling set point	76°F	77°F
Heating set point	72°F (6 AM – 8 AM); 69°F (8 AM – 6 AM)	73°F

Source: Gas Technology Institute

Figure 13 compares the modeled results and the utility data. Discrepancies were observed between the model results and utility data for both pre-retrofit period, represented by 2018, and post-retrofit period, represented by 2020. For example, the utility electricity data during the summers of 2018 and 2020 and the gas usage during January 2018 seem unusually low. Conversely, the BEopt model-predicted gas consumption did not show any increase during November and December 2020, which is unexpected due to space heating needs.

Figure 13: Comparison of Modeled and Utility Data - LFS



Source: Gas Technology Institute

Site NRB

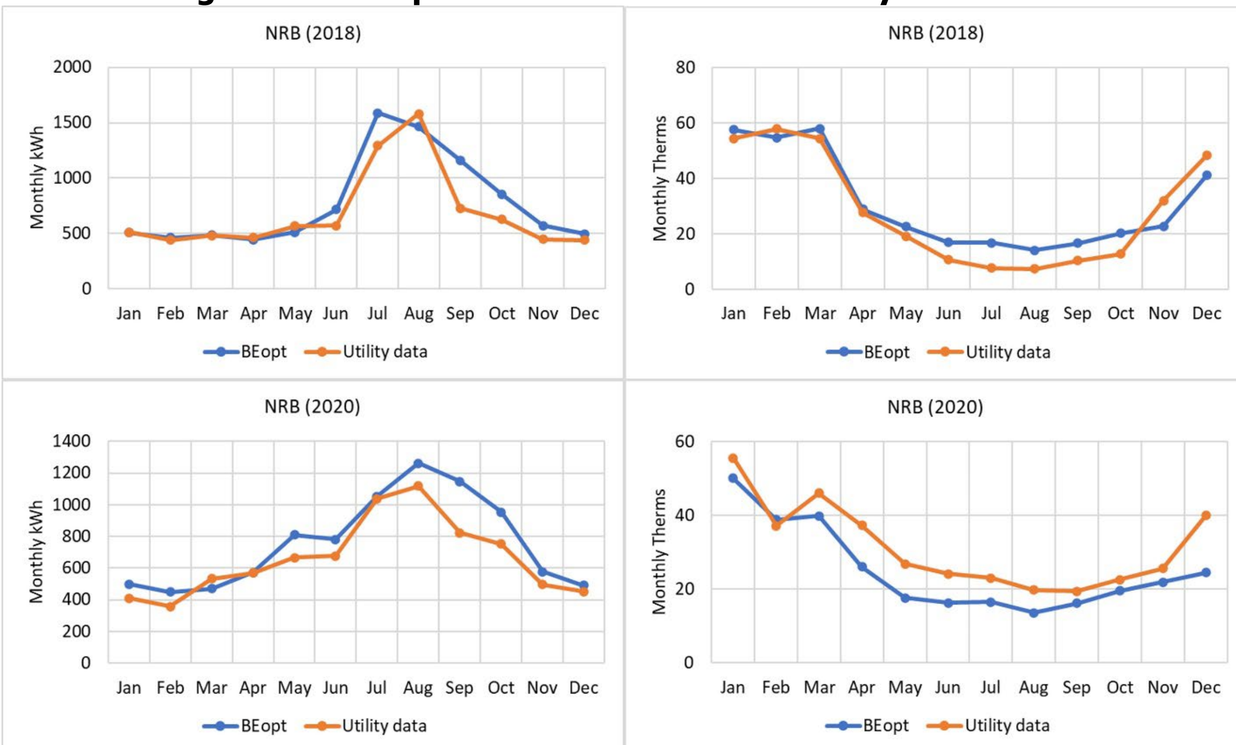
Table 18 lists the NRB building characteristics. No major air sealing was required or performed at the site, so the air exchange rate is listed as “unchanged” in the home upgrade report. However, the report noted that some improvement is expected due to the decreased leakage of the new duct system, so the model assumed 10 air changes per hour at 50 Pa pressure differential or ACH50 for post-retrofit air leakage. Figure 14 compares the modeled results and utility data for the pre-retrofit 2018 and post-retrofit 2020 periods. Good agreement was observed between the modeled results and utility data. The low-capacity system was switched from the low fire to the high fire stage during August 2020 and the appropriate low capacity system characteristics were assumed for the different months in 2020.

Table 17: Building Characteristics - NRB

	Prior	**Post-retrofit**
Furnace	75 kBtu/h, 78% AFUE	Low fire: 26 kBtu/h, 96.15% AFUE High fire: 40 kBtu/h, 97.5% AFUE
AC	3.5 tons, 10 SEER	Low fire: 1.5 tons, 16 SEER High fire: 2 tons, 16 SEER
Wall Insulation	None	None
Foundation Insulation	None	None
Roof/Attic Insulation	R-11 Fiberglass	R-38 Cellulose
Air Leakage (ACH50)	11.3	10.0 assumed
Duct Location, Insulation	Attic, R8	Attic, R8 buried ducts
Duct Leakage	30% total leakage	9% total leakage
Cooling set point	78°F	76°F
Heating set point	70°F	69°F

Source: Gas Technology Institute

Figure 14: Comparison of Modeled and Utility Data - NRB



Source: Gas Technology Institute

Site RPS

Like the LFS site, the team made assumptions for the leakage rates in RPS home for the post-retrofit period. This home received attic plane sealing and duct system replacement, which can be expected to lower the leakage rates. Further, the AC was not being used even after the HVAC replacement and an artificially high cooling set point was used in the model to preclude any cooling during the post-retrofit period. Figure 15 compares the modeled results with utility data. The electricity consumption showed some discrepancies during the 2020 post-retrofit period. The gas consumption showed reasonable agreement barring a few months, for example February 2018 and March 2020.

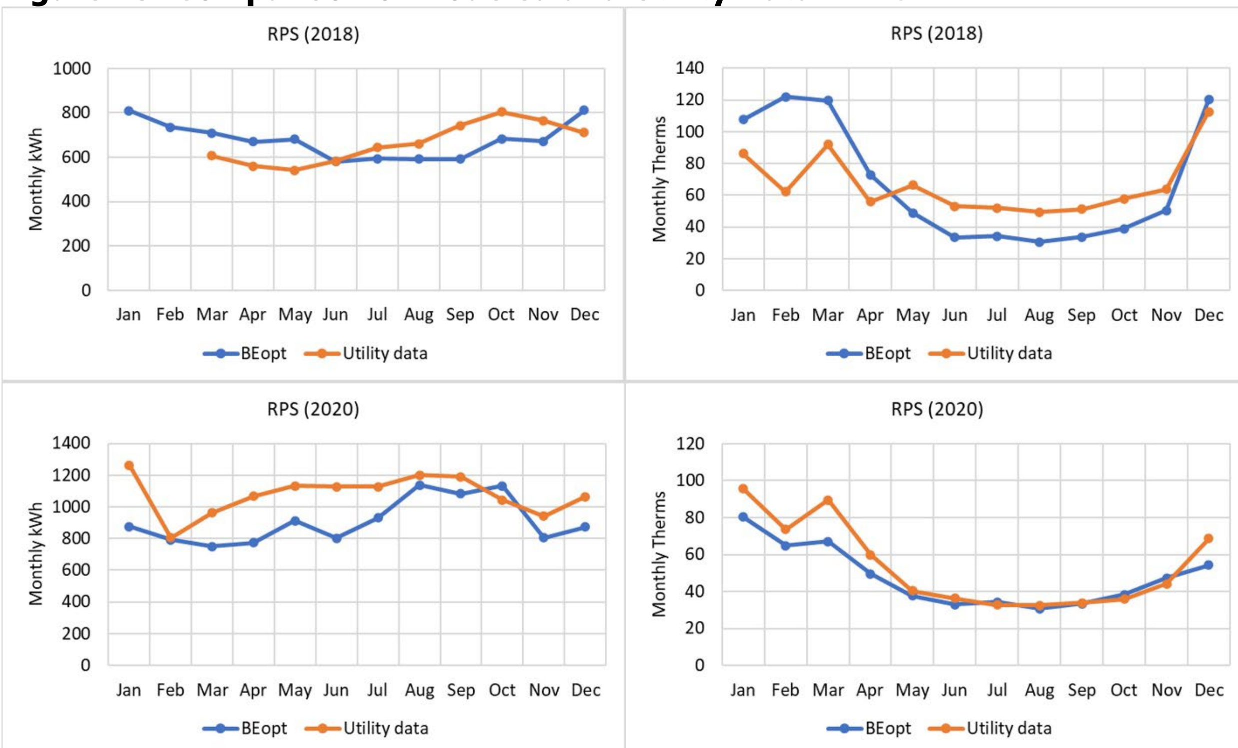
Table 18: Building Characteristics - RPS

	Prior	Post-retrofit
Furnace	125 kBtu/h, estimated 60% AFUE	26 kBtu/h, 96.15% AFUE
AC	No AC	1.5 tons, 16 SEER
Wall Insulation	R-11	R-11
Foundation Insulation	None	None
Roof/Attic Insulation	R-32	R-38
Air Leakage (ACH50)	32	Not tested; 32 assumed
Duct Location, Insulation	Attic, R4.2	Attic, R8 buried ducts

Duct Leakage	40% total leakage	Not tested; 0% to outside assumed
Cooling set point	Not applicable	74°F
Heating set point	68°F	70°F

Source: Gas Technology Institute

Figure 15: Comparison of Modeled and Utility Data - RPS



Source: Gas Technology Institute

Modeled Energy Savings

Following model calibration, the team used these models with TMY weather data as well as standard heating and cooling set points of 68°F and 78°F for estimating the energy savings. Table 20 shows the estimated energy savings across different sites resulting from the envelope upgrades and the HVAC replacement to the low capacity, high-efficiency furnace and AC system. Energy savings were calculated for the cooling electricity consumption, heating gas consumption and the electricity consumption of the fan during heating. It should be noted that the fan energy for heating is a small fraction of the overall energy consumption for space conditioning. "% Diff." refers to the change in energy consumption from the 'Prior' to the post-retrofit period and negative values indicate a reduction in energy use.

Table 19: Energy Performance Comparison Using TMY Weather Data

CMJ	**Prior**	**Post-retrofit**	**% Diff.**
Cooling (kWh)		686.9	
Heating (G) (kBtu)	2,306.2	2,154.3	-6.6%
Heating (fan) (kWh)	16.8	11.4	-32.3%
CVC	**Prior**	**Post-retrofit**	**% Diff.**
Cooling (kWh)	1,641.0	1,224.8	-25.4%

Heating (G) (kBtu)	3,740.5	2,464.2	-34.1%
Heating (fan) (kWh)	23.6	13.0	-44.9%
LFS	**Prior**	**Post-retrofit**	**% Diff.**
Cooling (kWh)	623.3	491.1	-21.2%
Heating (G) (kBtu)	3,360.6	1,129.0	-66.4%
Heating (fan) (kWh)	17.6	5.9	-66.3%
NRB	**Prior**	**Post-retrofit**	**% Diff.**
Cooling (kWh)	2,487.6	1,351.7	-45.7%
Heating (G) (kBtu)	13,315.1	7,530.4	-43.4%
Heating (fan) (kWh)	97.1	40.6	-58.2%
RPS	**Prior**	**Post-retrofit**	**% Diff.**
Cooling (kWh)		526.6	
Heating (G) (kBtu)	34,721.8	10,036.7	-71.1%
Heating (fan) (kWh)	48.5	52.8	8.9%

Source: Gas Technology Institute

The average estimated energy savings for cooling and heating across the different sites were 31 percent and 44 percent, respectively. The savings varied appreciably across sites, which is according to expectations. For example, site CMJ had received a well-executed home energy retrofit in 1992 and thus did not require many incremental measures within this project. In contrast, LFS and RPS received substantial upgrades to the existing envelope system, such as upgraded attic insulation and attic plane sealing. Further, the RPS site featured an original 1950s furnace. The estimated savings reflect the pre- and post-retrofit characteristics of the homes.

Site Testing, Data Monitoring and Analysis Results

Site data collection began in August 2019, shortly after installation of the low-capacity HVAC system and envelope retrofits. At most sites, the new system was locked in the LO fire stage initially, and then switched over to the HI fire stage during December 2020. It should be noted that at one site, CMJ, the system was inadvertently allowed to modulate between HI and LO fire in the first monitoring period, so at the switch-over point, it was set to LO fire so that this important mode could be analyzed. This made it impossible to conduct the same HI/LO comparisons as the other sites, and for this reason, this site is not included in some of the analysis. At NRB, the switchover from LO to HI fire occurred in August 2020.

One-time Field Tests

Field measurements of supply and return temperatures, air flow rates and temperature stratification were performed at all sites and are described in the following sections.

Heating and Cooling Rates

Table 21 and Table 22 list the measurements and resulting energy delivery rates for both cooling and heating for all sites. Equation 2 was used to calculate the energy delivery rates. These tables also show the rated capacities at HI and LO fire, as well as the "Turn Down" ratio, that is the ratio of capacities at HI and LO fire. Because site CMJ was allowed to modulate between HI and LO fire, the data from that site are not included in the averages.

These tables show that the measured capacity of the systems was less than the rated capacity in all cases. This is expected, because the operation is seldom at the full rated conditions and due to measurement uncertainties. It was reassuring to note that the estimated average turn-down-ratios were close to the ratings.

Table 20: Cooling One-Time Supply and Return Temperature and CFM Measurements, and Resulting Energy Delivery Rate for HI and LO Fire

Site	HI - T_{SUP} (°F)	HI - T_{RET} (°F)	HI - CFM	HI - Rate (kBtu/h)	LO - T_{SUP} (°F)	LO - T_{RET} (°F)	LO - CFM	LO - Rate (kBtu/h)	TURN DOWN
CMJ	45.6	70.4	741	19.8	47.5	65.7	710	14.0	1.41
CVC	43.4	60.0	598	10.7	39.8	70.0	335	11.6	0.92
LFS	44.1	72.0	629	18.9	48.6	75.0	365	10.4	1.82
NRB	45.3	70.0	712	19.0	50.7	70.0	780	16.3	1.17
RPS	41.1	71.5	702	23.0	46.6	67.7	537	12.2	1.89
AVG				17.9				12.6	1.42
Rated				24.0				18.0	1.33

Source: Frontier Energy

Table 21: Heating One-Time Supply and Return Temperature and CFM Measurements, and Resulting Energy Delivery Rate for HI and LO Fire

Site	HI - T_{SUP} (°F)	HI - T_{RET} (°F)	HI - CFM	HI - Rate (kBtu/h)	LO - T_{SUP} (°F)	LO - T_{RET} (°F)	LO - CFM	LO - Rate (kBtu/h)	TURN DOWN
CMJ	110.5	77.1	889	32.1	98.4	67.8	682	22.6	1.42
CVC	98.8	71.5	786	23.2	94.8	72.0	612	15.1	1.54
LFS	114.4	71.0	700	32.8	110.6	73.0	449	18.2	1.80
NRB	118.0	70.0	809	41.9	110.0	70.0	657	28.4	1.48
RPS	101.3	75.0	677	19.3	93.0	70.0	479	11.9	1.62
AVG				29.3				18.4	1.59
Rated				39.0				25.0	1.56

Source: Frontier Energy

Temperature Stratification

Table 23 and Table 24 show how the floor and ceiling temperatures compared to the mid-level during heating and cooling, respectively, during low-capacity operation.

Negative values - shown in parentheses - indicate that the temperature was lower than mid-level. Lower temperature stratification was observed in the heating mode with the new HVAC system at LO fire than the prior system; stratification data for the prior system in cooling mode was not available for comparison.

Table 22: Stratification During Heating

SITE	Floor (to mid)	Floor (to mid)	Ceiling (to mid)	Ceiling (to mid)	Ceiling (to floor)	Ceiling (to floor)	Prior System - Ceiling (to floor)
CMJ	*Kit*	*Hall*	*Kit*	*Hall*	*Kit*	*Hall*	
	(5.3)	(2.8)	(0.8)	(0.2)	4.5	2.6	4.2
CVC	*LR*	*Bed*	*LR*	*Bed*	*LR*	*Bed*	
	(1.2)	(0.1)	3.0	(2.1)	4.2	(2.0)	8.7
LFS	*LR*	*Hall*	*LR*	*Hall*	*LR*	*Hall*	
	(3.2)	(3.9)	1.4	2.6	4.6	6.5	6.5
NRB	*Kit*	*Hall*	*Kit*	*Hall*	*Kit*	*Hall*	
	(5.1)	(3.7)	1.5	1.3	6.6	5.0	12.0
RPS	*LR*	*Hall*	*LR*	*Hall*	*LR*	*Hall*	
	(2.9)	(3.3)	(0.9)	0.5	2.0	3.8	N/A

Temperatures compared to thermostat height or floor.

Source: Frontier Energy

Table 23: Stratification During Cooling

SITE	Floor (to mid)	Floor (to mid)	Ceiling (to mid)	Ceiling (to mid)	Ceiling (to floor)	Ceiling (to floor)
CMJ	*Kit*	*Hall*	*Kit*	*Hall*	*Kit*	*Hall*
	(1.9)	(2.3)	1.1	3.3	3.0	5.6
CVC	*LR*	*Bed*	*LR*	*Bed*	*LR*	*Bed*
	(1.1)	(2.5)	3.4	(0.8)	4.5	1.7
LFS	*LR*	*Hall*	*LR*	*Hall*	*LR*	*Hall*
	(0.8)	(1.1)	0.6	(0.3)	1.4	0.8
NRB	*Kit*	*Hall*	*Kit*	*Hall*	*Kit*	*Hall*
	(0.8)	(1.3)	0.1	2.6	0.9	3.9
RPS	*LR*	*Hall*	*LR*	*Hall*	*LR*	*Hall*
	(0.3)	(1.2)	0.4	0.5	0.7	1.7

Temperatures compared to thermostat height or floor.

Source: Frontier Energy

Monitored Data and HVAC Performance

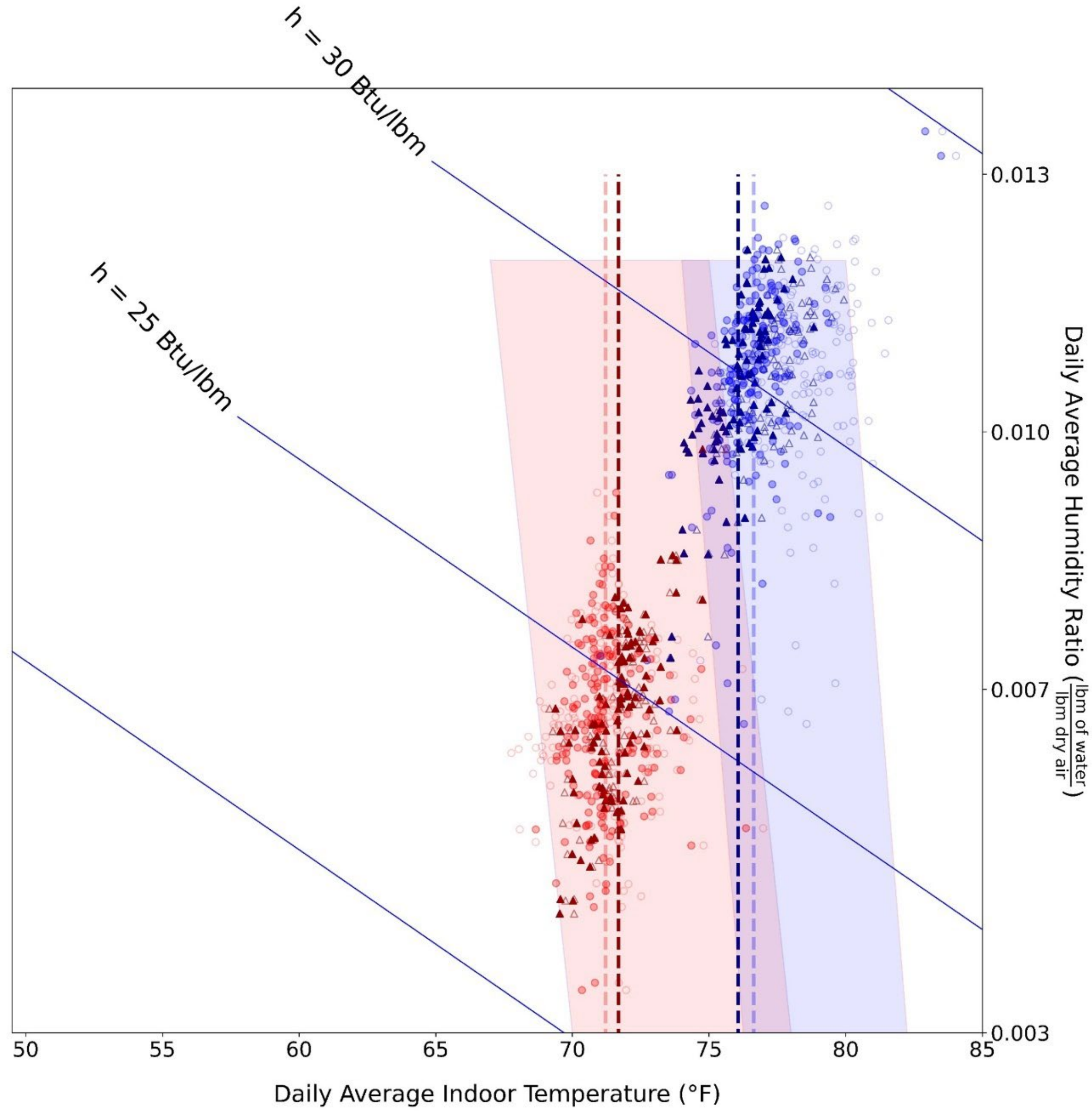
Following sections describe the key parameters that were monitored and analyzed to understand the HVAC performance and comfort conditions at all test sites. For much of the discussion in this section, data is shown first for the LFS site as an example, and then for the remaining sites.

Comfort Conditions

Figure 16 shows the daily average temperature and RH measured at one site. The results are shown only for hours with cooling and heating operation. In this and most charts that follow, dark triangles represent HI fire operation, and lighter circles represent LO fire. Red/pink markers indicate heating, and dark/light blue are cooling. This chart also includes open circles and triangles, which represent the conditions at any remote temperature sending units, typically bedrooms. The vertical dotted lines represent the average temperature setpoint when the system was running. These measured data points are superimposed on the ASHRAE comfort zones to gauge whether the measured conditions would be considered comfortable. Figure 17 shows the comfort charts for the remaining sites.

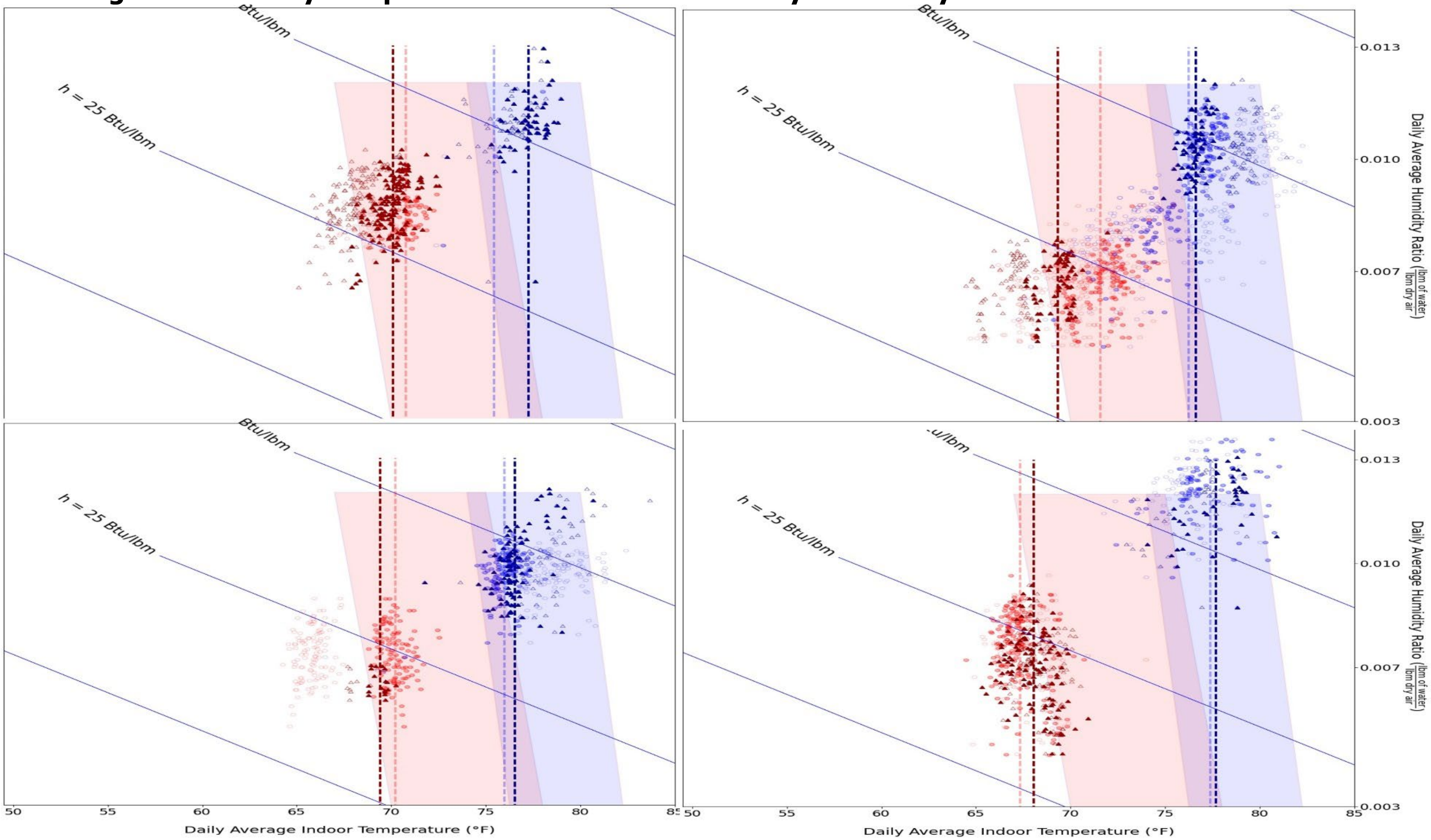
These charts show that most of the operation was within the ASHRAE comfort zone. Conditions in bedrooms were the most likely to be outside the comfort zone. The conditions did show a fair amount of scatter, but tended to be clustered around the setpoint. In several cases, setpoints were at the edges of the comfort zone, and one would not expect all points to be within the comfort zone. For example, at RPS, many heating temperature points were below the comfort zone, although the setpoint was also low, indicating that the system operated as the occupants expected.

Figure 16: Hourly Temperature and Relative Humidity at Primary Thermostat and Remote Sensors - LFS



Source: Frontier Energy

Figure 17: Hourly Temperature and Relative Humidity at Primary Thermostat and Remote Sensors



Clockwise from top left: CMJ, CVC, RPS, NRB.

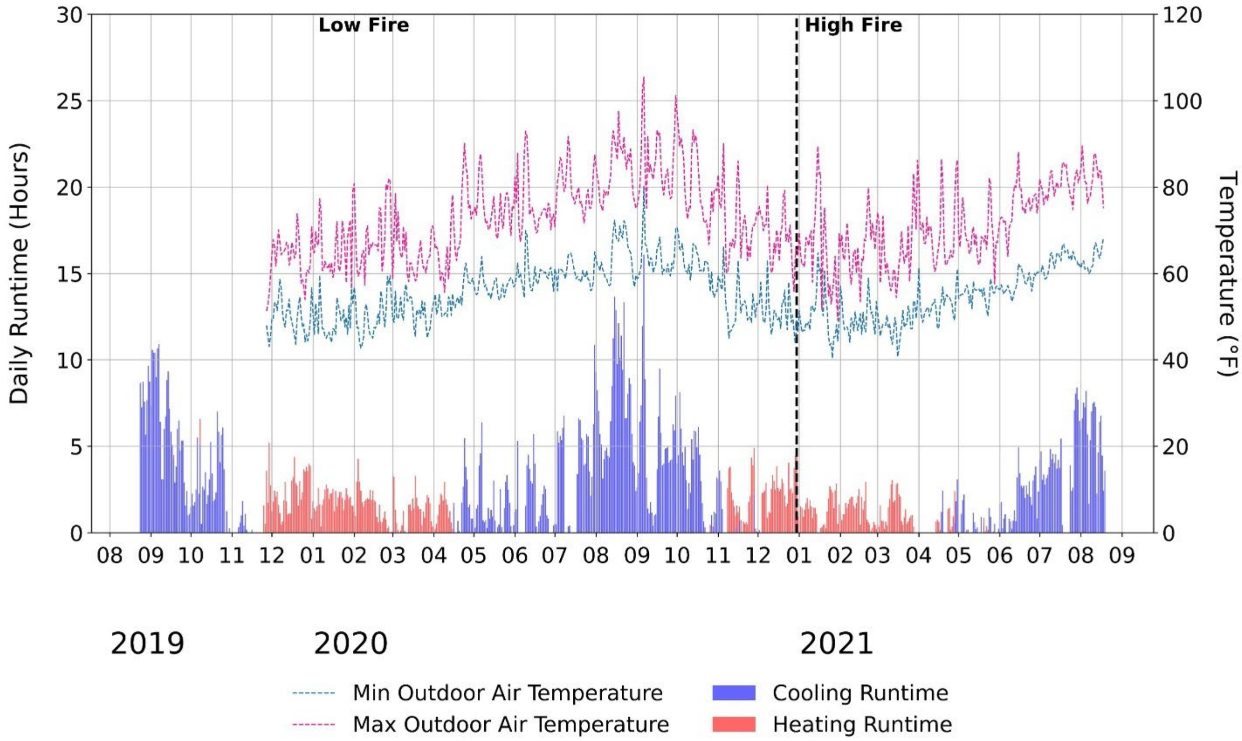
Source: Frontier Energy

Runtime

Runtime was expected to be higher for a lower capacity system. Runtime for the system in cooling or heating mode was inferred by analyzing both the gas and electric consumption and the system mode, as recorded by the Ecobee thermostats. These thermostats reported the number of seconds that the system was calling for cooling or heating during every five-minute period. The five-minute totals could be summed across an hour, day, or month to calculate runtime. Figure 18 and Figure 19 illustrate this data for the different sites.

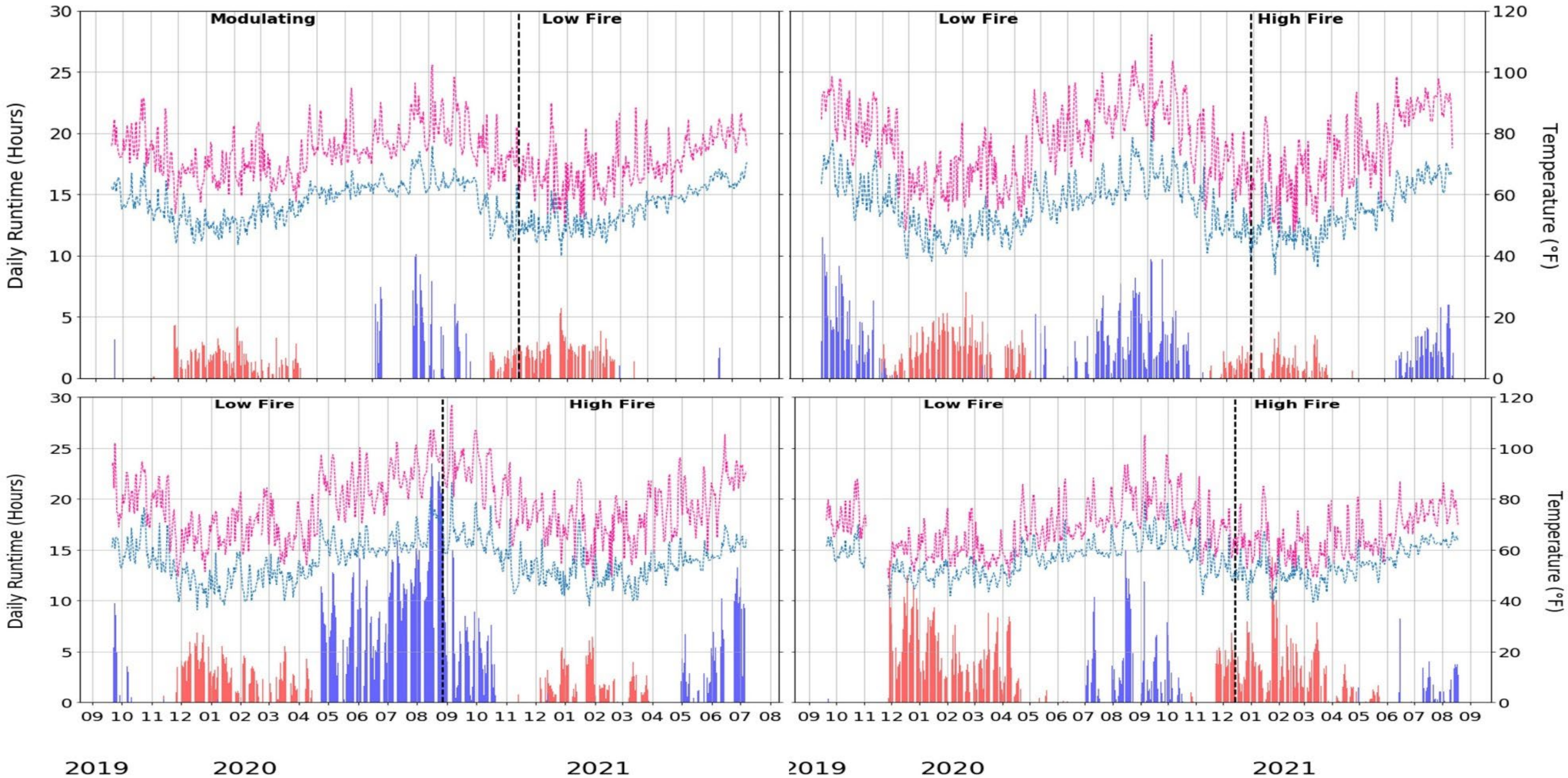
For heating, the runtime was lower at HI fire, as expected.

Figure 18: Cooling and Heating Runtimes: Hours Per Day - LFS



Source: Frontier Energy

Figure 19: Cooling and Heating Runtimes: Hours Per Day



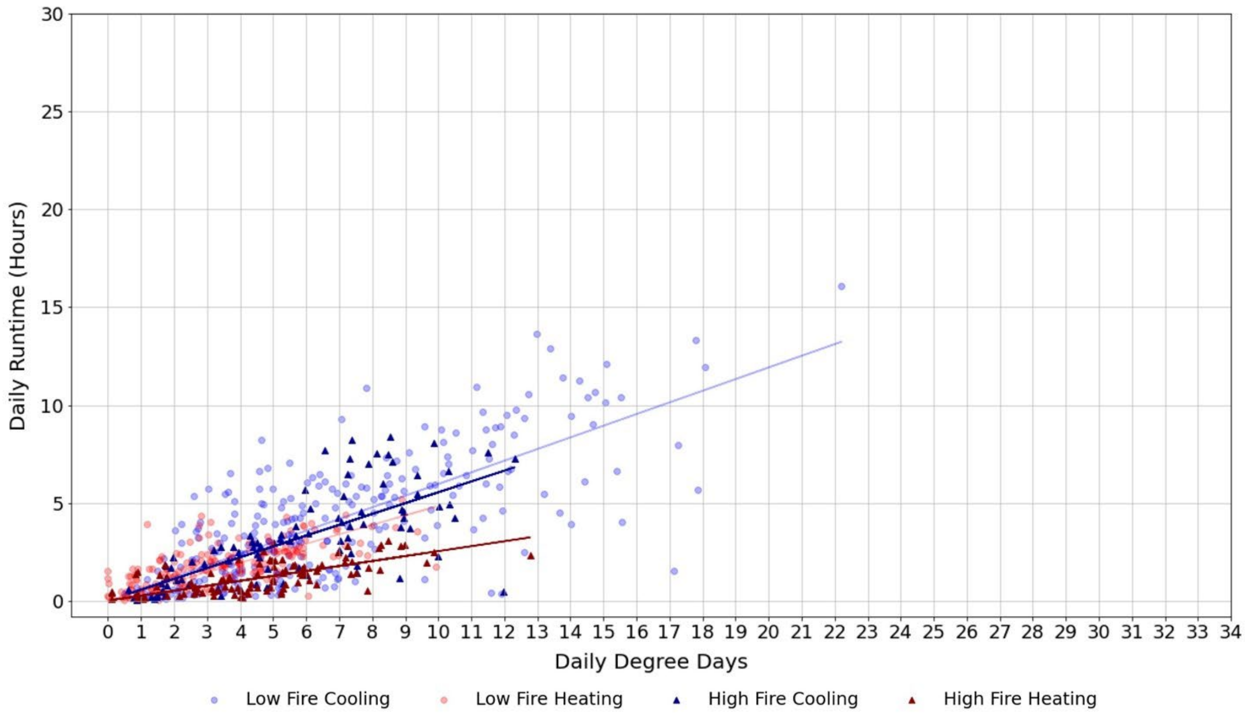
Clockwise from top left: CMJ, CVC, RPS, NRB

Source: Frontier Energy

Figure 20 and Figure 21 show this same information as the previous charts but are graphed as functions of daily Degree Days, either CDD or HDD, as appropriate. The slope of each trendline indicates the number of hours that the system must run per degree-day. Table 25 and Figure 22 compare these slopes for each site and shows how the slopes, shown as minutes of operation per degree-day or Min/DD, compared between HI and LO fire modes.

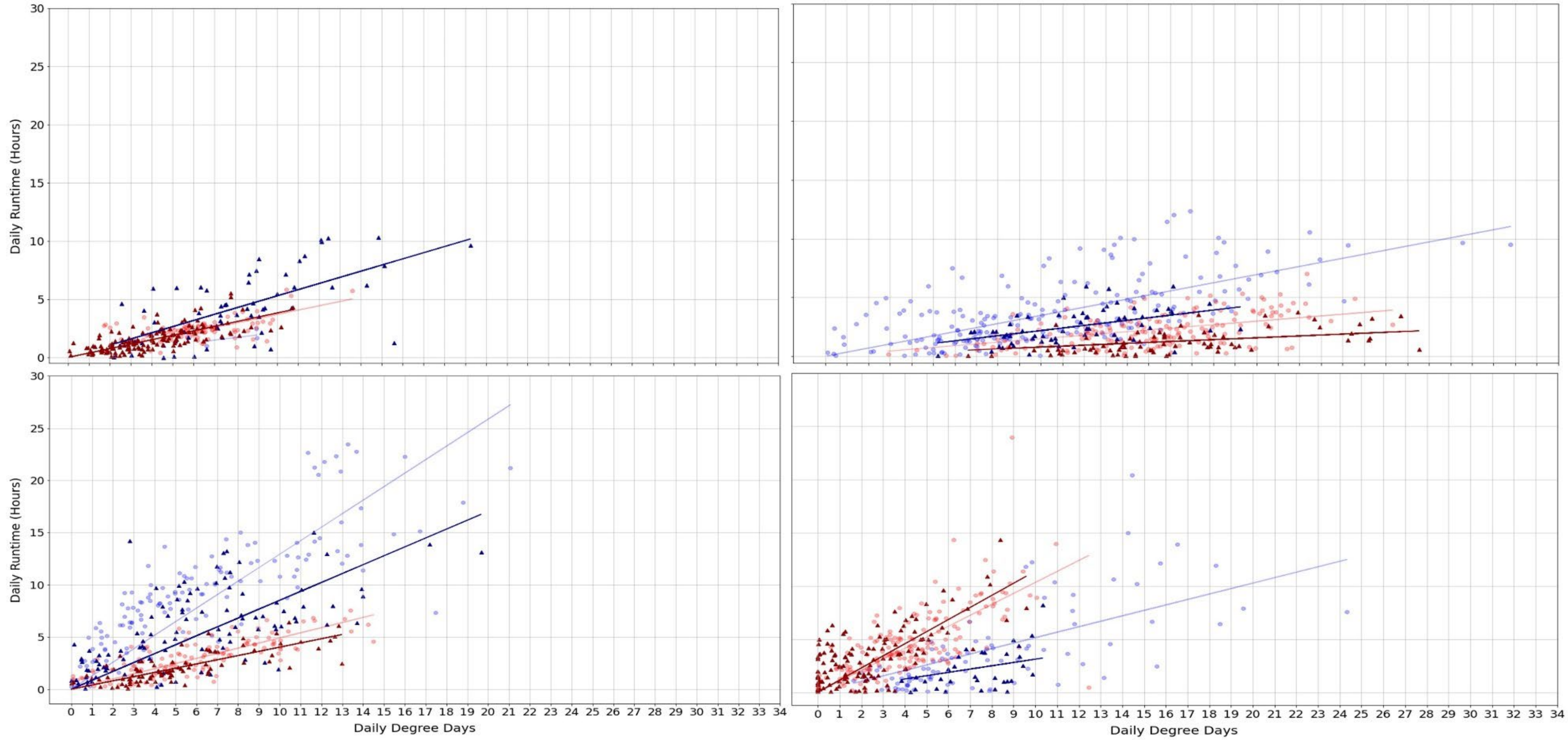
These charts show that, for a given degree-day level, the runtime at HI fire was about two-thirds of what it was for LO fire, as expected.

Figure 20: Daily Cooling and Heating Runtime Per Degree Day - LFS



Source: Frontier Energy

Figure 21: Daily Cooling and Heating Runtime Per Degree-Day



Clockwise from top left: CMJ, CVC, RPS, NRB

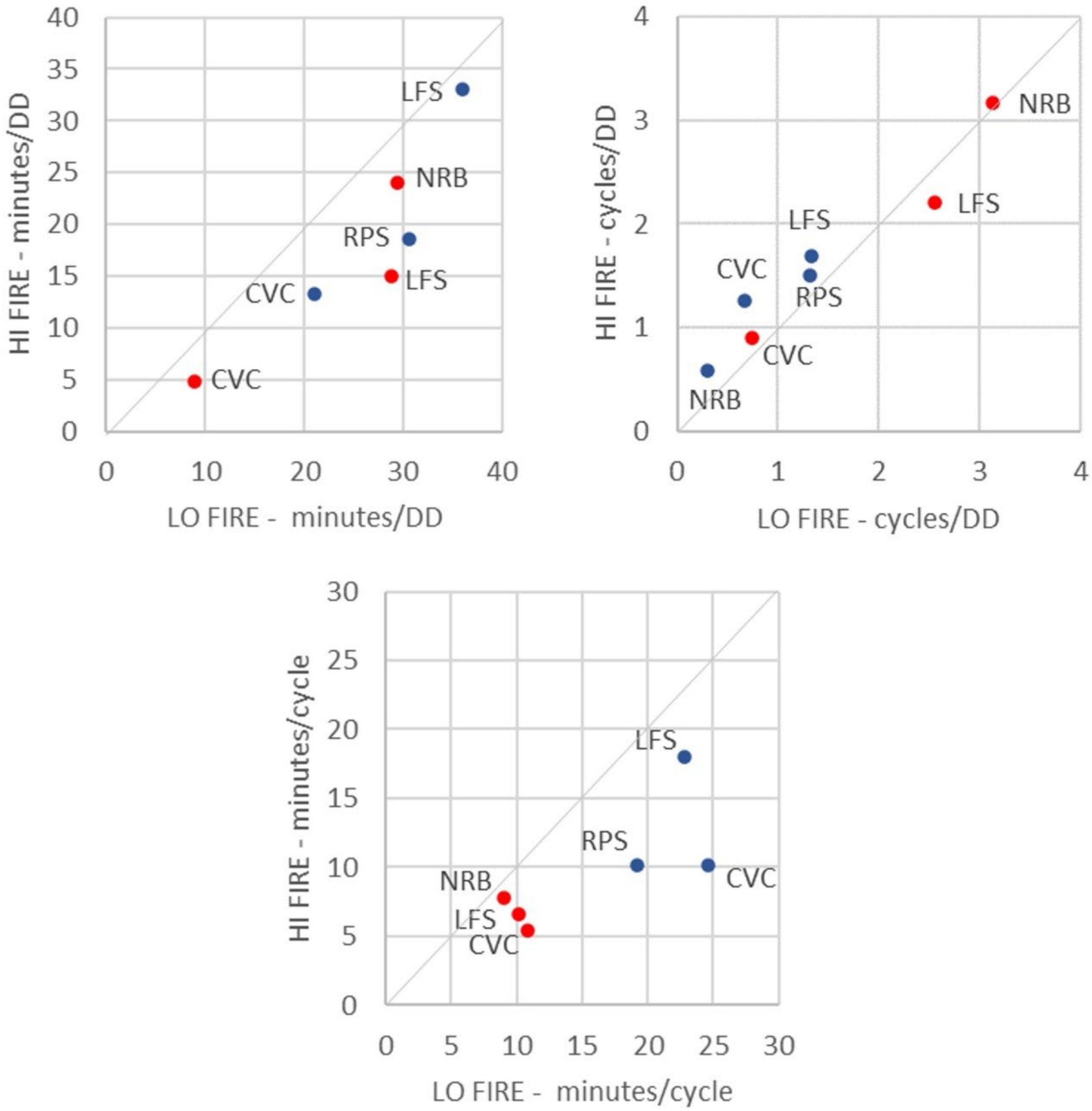
Source: Frontier Energy

Table 24: Summary of Operation per Degree Day

		Min/DD – Heating - HI	Min/DD – Heating -LO	HI/LO	Min/DD – Cooling -HI	Min/DD – Cooling -LO	HI/LO		Cycles/DD – Heating - HI	Cycles/DD – Heating - LO	HI/LO	Cycles/DD – Cooling - HI	Cycles/DD – Cooling - LO	HI/LO		Min/Cycle – Heating - HI	Min/Cycle – Heating - LO	HI/LO	Min/Cycle – Cooling - HI	Min/Cycle – Cooling -LO	HI/LO
CMJ		*23*	*22*	*1.03*	*32*	*13*	*2.52*		*2.7*	*1.0*	*2.69*	*1.5*	*0.3*	*5.32*		*7*	*15*	*0.48*	*19*	*39*	*0.49*
CVC		5	9	0.53	13	21	0.63		0.9	0.8	1.20	1.3	0.7	1.88		5	11	0.50	10	25	0.41
LFS		15	29	0.52	33	36	0.92		2.2	2.6	0.87	1.7	1.3	1.27		7	10	0.65	18	23	0.79
NRB		24	29	0.82	*51*	*77*	*0.66*		3.2	3.1	1.01	0.6	0.3	1.97		8	9	0.87	*54*	*118*	*0.46*
RPS		*68*	*62*	*1.11*	19	31	0.61		*3.4*	*1.2*	*2.79*	1.5	1.3	1.14		*17*	*33*	*0.51*	10	19	0.53
AVG*		**15**	**22**	**0.65**	**22**	**29**	**0.74**		**2.1**	**2.1**	**0.98**	**1.3**	**0.9**	**1.39**		**7**	**10**	**0.66**	**13**	**22**	**0.58**

Source: Frontier Energy

Figure 22: Minutes/DD, Cycles/DD and Minutes/Cycle During HI and LO Fire

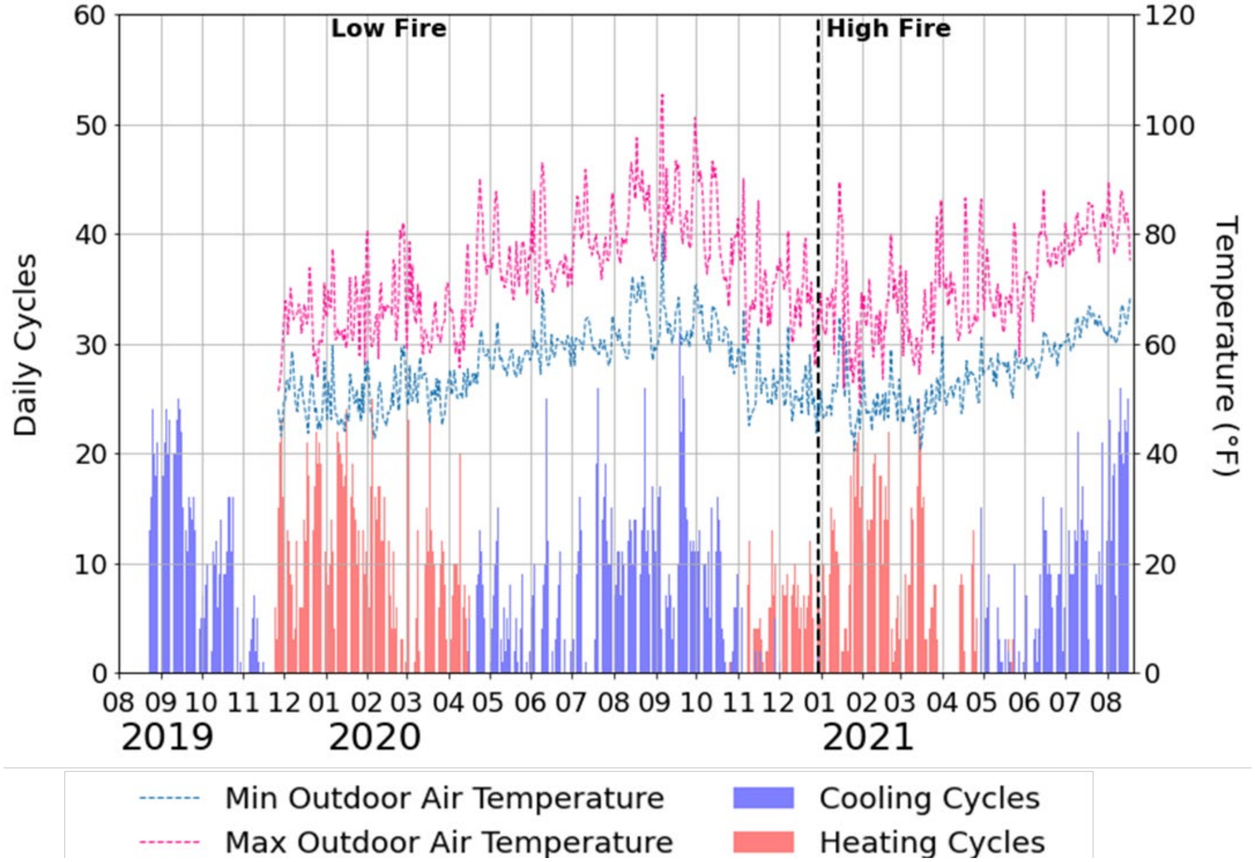


Source: Frontier Energy

Cycling

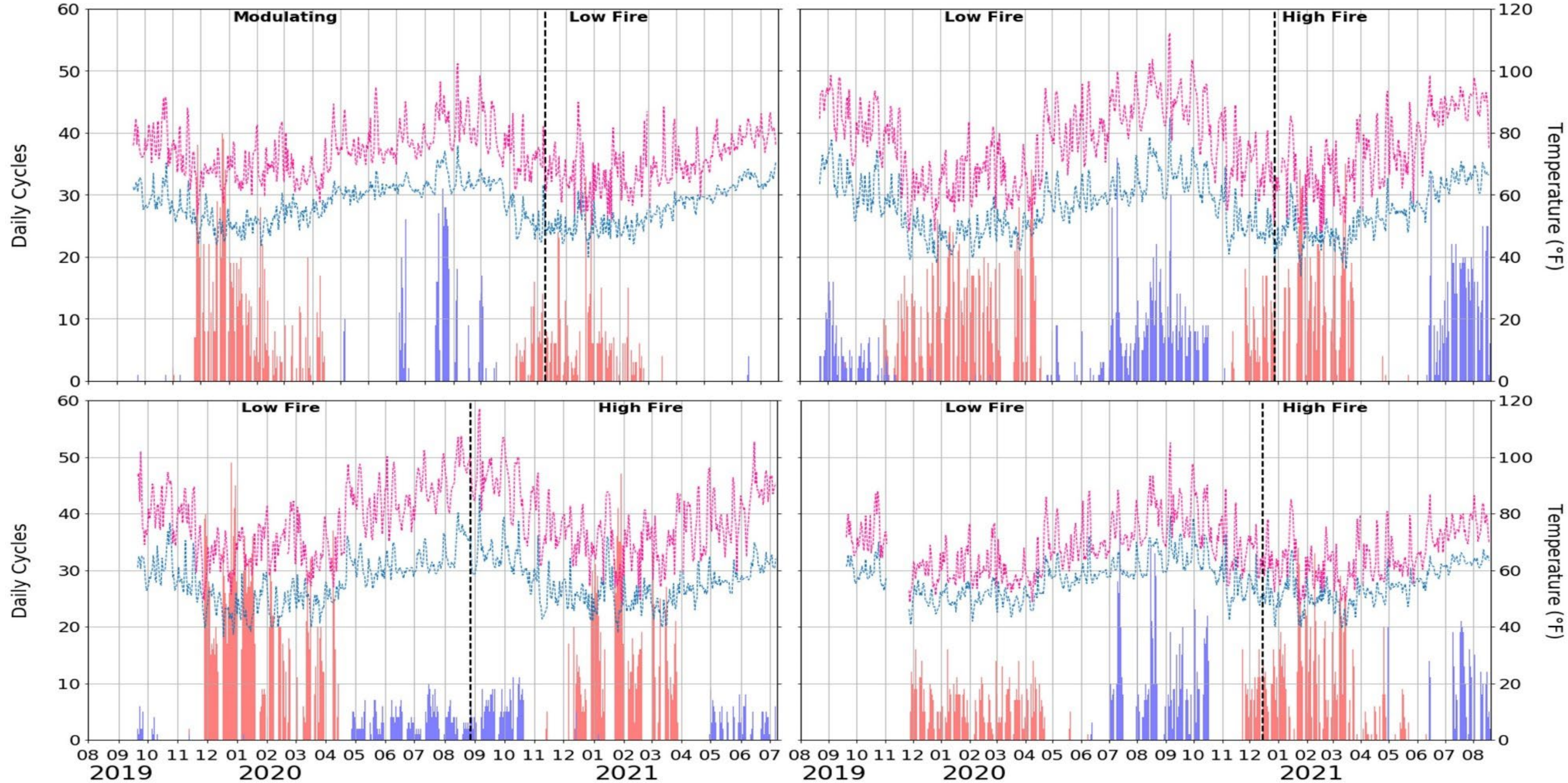
System cycling was expected to be affected by the capacity setting of the system. Cycles were determined by analyzing 15-second gas or outdoor-unit electricity consumption and by detecting how many times per day the system transitioned from OFF, that is zero energy consumption for at least a minute, to ON or a non-zero reading. Figure 23 and Figure 24 illustrate the total cooling and heating cycles per day. These charts also show the daily minimum and maximum outdoor air temperatures. The dotted vertical line indicates when the system was switched from LO to HI fire. For both heating and cooling, the systems typically cycled on and off about five to fifteen times per day. There did not appear to be a large difference between LO and HI fire operation.

Figure 23: Cooling and Heating Cycles Per Day - LFS



Source: Frontier Energy

Figure 24: Cooling and Heating Cycles Per Day



Clockwise from top left: CMJ, CVC, RPS, NRB

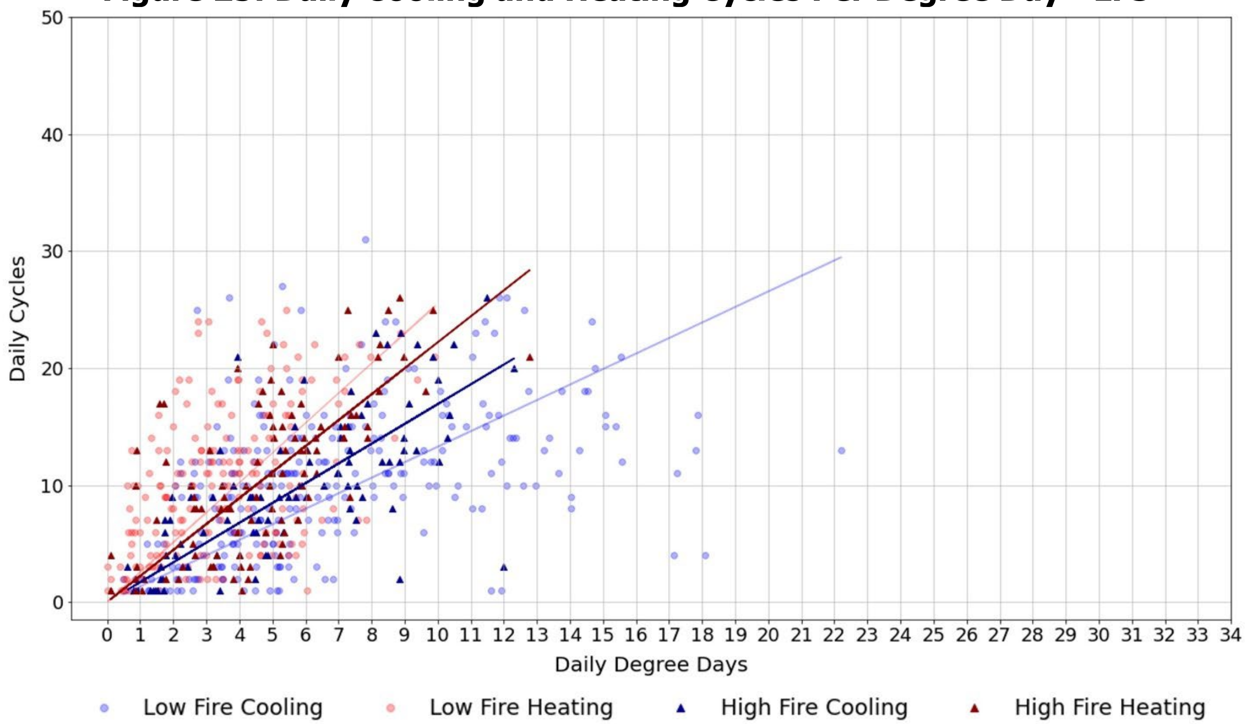
Source: Frontier Energy

Figure 25 and Figure 26 show the same information as the previous charts but are graphed as functions of the daily Degree Days, either CDD or HDD, as appropriate. The degree day data is described in more detail in a later section. The slope of each trendline indicates the number of cycles per degree-day. Table 25 compared these slopes for each site and shows how the slopes, that is cycles per degree-day compare between HI and LO fire.

These charts show that for heating, in some cases, there were more cycles per degree day at HI fire than LO fire, but for others it was reversed. For cooling, there was more consistency and there were 29 percent more cycles at HI fire than LO.

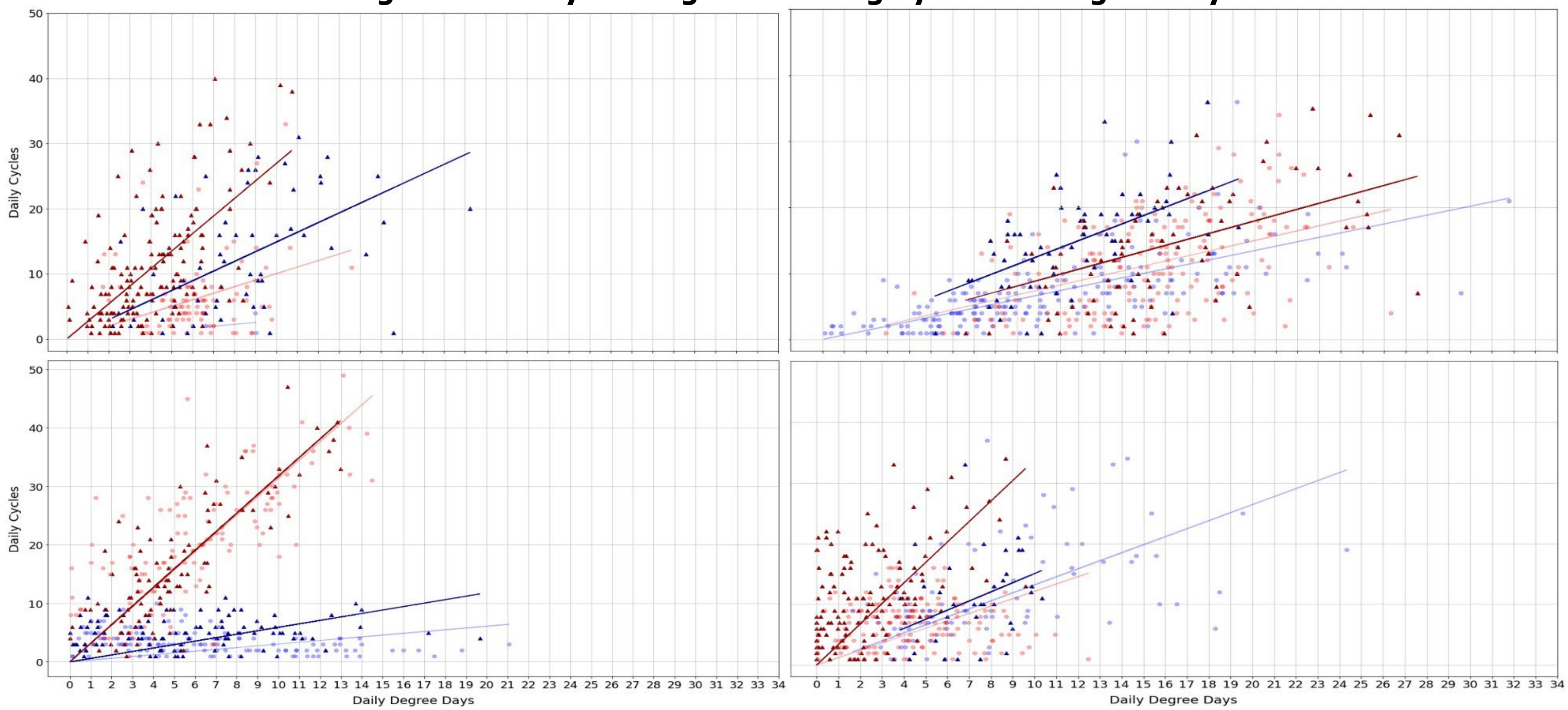
It is unclear whether to expect more cycles at HI fire than LO. Although a system at LO fire that is working hard to keep up with loads will cycle less, the cycles are also influenced by the envelope and how quickly the thermostat set point becomes unsatisfied.

Figure 25: Daily Cooling and Heating Cycles Per Degree Day - LFS



Source: Frontier Energy

Figure 26: Daily Cooling and Heating Cycles Per Degree-Day



Clockwise from top left: CMJ, CVC, RPS, NRB

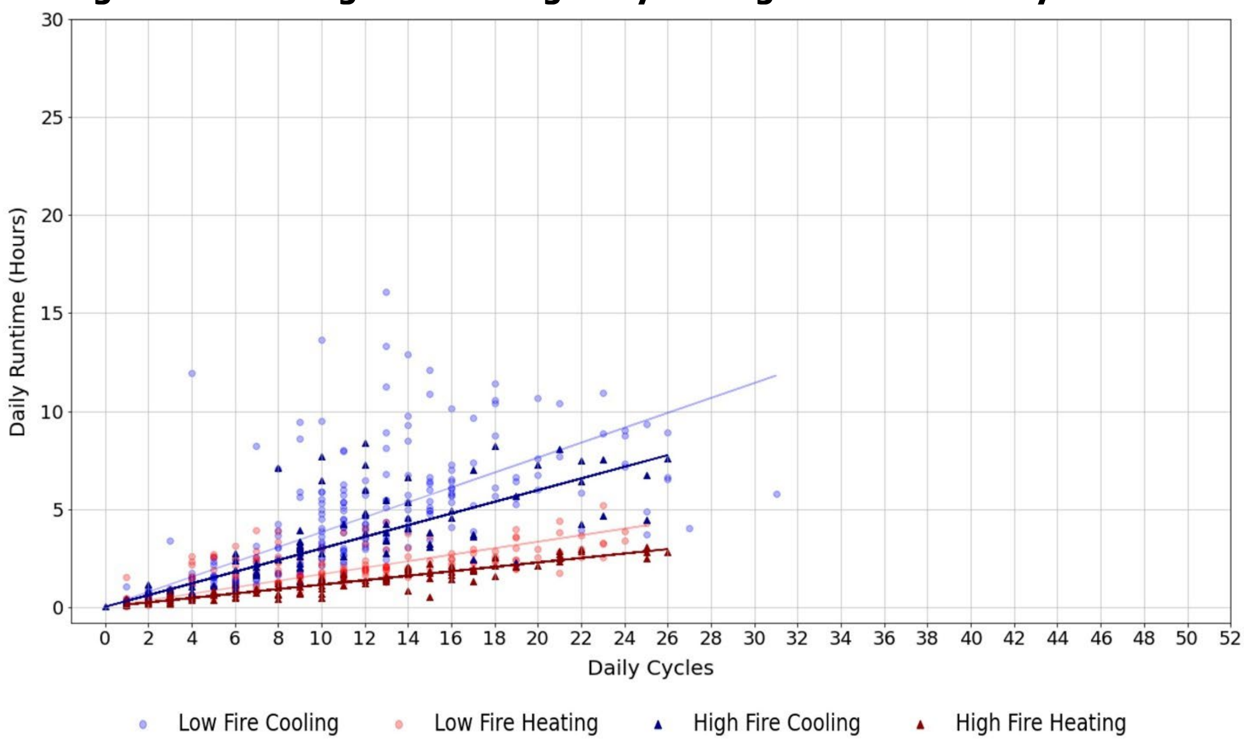
Source: Frontier Energy

Length of Cycles

Figure 27 and Figure 28 combine the data from the previous two analyses, by showing daily runtime as a function of daily cycles. In these figures, the slope of each line indicates the average length of each cycle. Table 25 compares these slopes for each site and shows how the slopes, shown as minutes per cycle, compare between HI and LO fire.

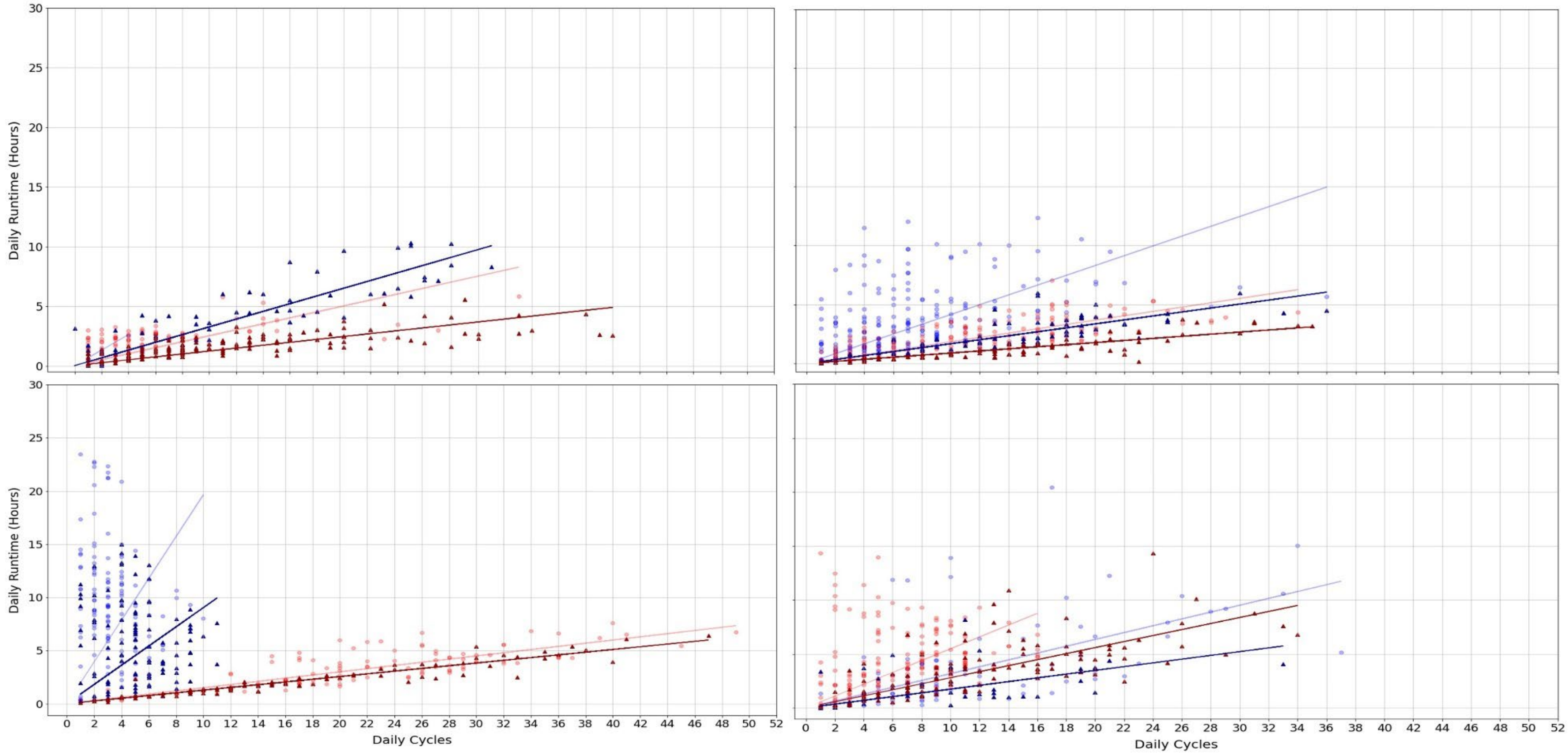
The minutes per cycle ranged from about 5 to 11 for heating and 10 to 25 for cooling, and runtime per cycle at HI fire was about half that of LO fire.

Figure 27: Cooling and Heating Daily Average Runtime Per Cycle - LFS



Source: Frontier Energy

Figure 28: Cooling and Heating Daily Average Runtime Per Cycle



Clockwise from top left: CMJ, CVC, RPS, NRB

Source: Frontier Energy

Delivered Energy and Energy Consumption

One-time measurements of supply and return air temperatures and RH, and airflow rates with the unit in full cooling and full heating modes were used to estimate the rate of energy delivered. The total amount of energy delivered in an hour, day, or month was calculated by multiplying this rate of energy delivery by the runtime during the corresponding time period. The energy delivery data in Table 26 are normalized to average daily values. In this table, values representing operation at HI fire are in bold text and values representing operation at LO fire are in italicized text. The averages shown are based on only the non-zero values.

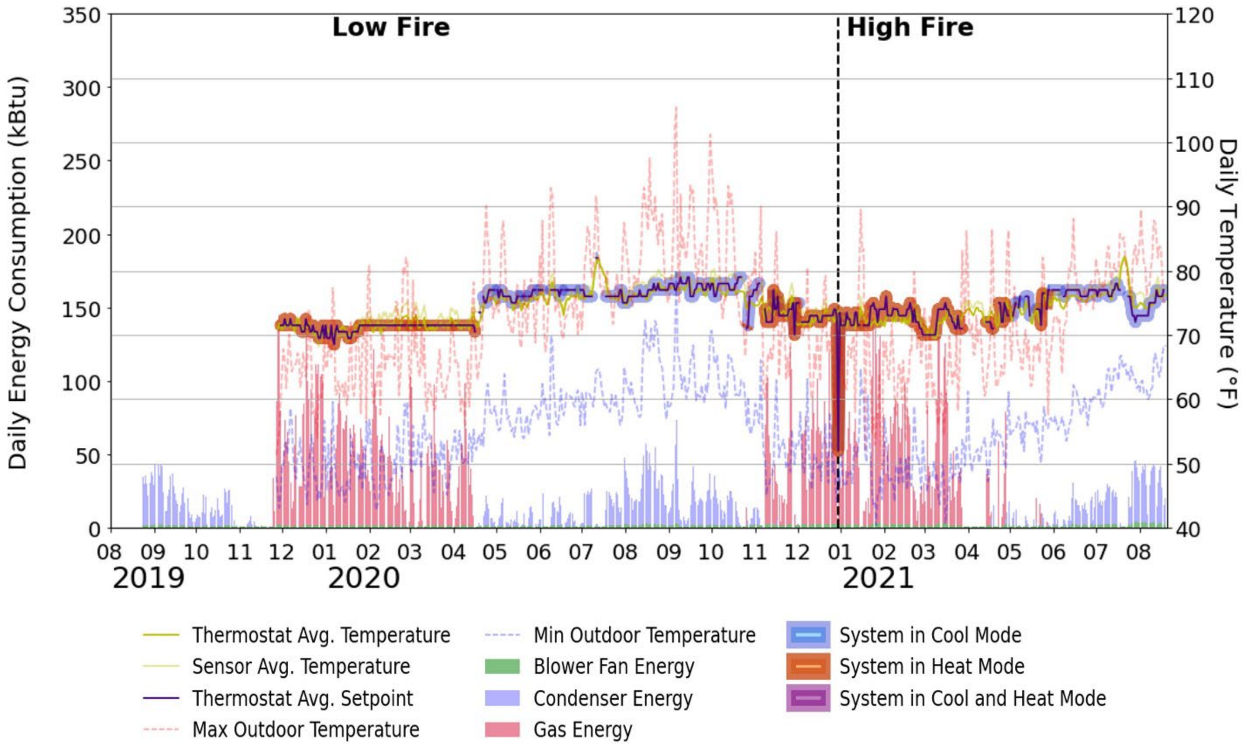
Table 25: Monthly Cooling and Heating Energy Delivery in Average kBtu/day

MONTH	CMJ - COOL	CMJ - HEAT	CVC - COOL	CVC - HEAT	LFS - COOL	LFS - HEAT	NRB - COOL	NRB - HEAT	RPS - COOL	RPS - HEAT
AUG ‘19	-	-	*112.2*	-	*95.1*	-	-	-	-	-
SEP ‘19	**8.8**	-	*59.1*	*0.1*	*62.0*	*0.0*	*75.4*	-	*0.5*	-
OCT ‘19	**0.8**	-	*23.9*	*0.5*	*29.2*	*0.0*	*6.1*	-	-	-
NOV ‘19	**0.0**	**17.0**	*3.1*	*12.7*	*1.9*	*8.5*	*0.2*	*21.6*	-	*10.2*
DEC ‘19	-	**63.4**	*0.9*	*37.0*	-	*42.5*	-	*129.7*	-	*90.4*
JAN ‘20	-	**58.7**	*0.1*	*48.6*	-	*34.9*	*0.1*	*76.8*	-	*61.3*
FEB ‘20	-	**41.6**	*0.5*	*36.8*	-	*27.7*	-	*52.3*	-	*28.5*
MAR ‘20	-	**25.0**	-	*10.2*	-	*23.1*	-	*46.8*	-	*47.0*
APR ‘20	-	**12.0**	*3.4*	*4.6*	*8.3*	*11.8*	*32.0*	*12.2*	-	*29.0*
MAY ‘20	**2.5**	-	*6.1*	-	*15.1*	-	*100.2*	-	-	*1.6*
JUN ‘20	-	-	*9.2*	-	*17.5*	-	*115.9*	-	*0.1*	*0.1*
JUL '20	**30.3**	-	*34.9*	-	*36.7*	-	*178.1*	-	*23.0*	-
AUG '20	**73.5**	-	*54.4*	-	*78.9*	-	*213.8*	-	*61.6*	-
							14.0	-		
SEP '20	**29.9**	-	*39.8*	-	*51.6*	-	**114.7**	-	*41.0*	-
OCT '20	**23.4**	-	*18.8*	-	*32.0*	*0.3*	**75.4**	-	*14.6*	*0.6*
NOV ‘20	-	**26.8**	*0.2*	*5.8*	*5.0*	*23.3*	-	**1.0**	-	*13.4*
DEC '20	-	**13.1**	-	*15.8*	*0.1*	*36.7*	**0.5**	**33.3**	-	*17.5*
	-	*30.6*	-	-	-	-			-	**40.3**
JAN '21	-	*48.1*	-	**23.4**	-	**45.2**	**0.1**	**58.4**	-	**84.4**
FEB ‘21	-	*32.3*	-	**19.2**	-	**44.1**	-	**30.4**	-	**59.0**
MAR ‘21	*0.4*	*26.0*	-	**24.4**	-	**37.8**	-	**52.7**	-	**58.4**
APR ‘21	-	*1.0*	-	**0.5**	**5.7**	**9.2**	**1.2**	-	**1.1**	**16.3**
MAY ‘21	-	-	-	**0.0**	**7.5**	**1.1**	**36.2**	-	-	**4.9**
JUN ‘21	-	-	**9.6**	-	**35.7**	-	**91.7**	-	**7.1**	**0.1**
JUL '21	*1.9*	-	**28.6**	-	**70.2**	-	**41.4**	-	**27.3**	-
AUG '21	-	-	**20.3**	-	**66.1**	-	-	-	**26.7**	-
Low AVG	***1.2***	***27.6***	***24.4***	***17.2***	***33.3***	***19.0***	***80.2***	***56.5***	***23.5***	***27.2***
High AVG	***21.2***	***32.2***	***19.5***	***13.5***	***37.1***	***27.5***	***41.7***	***35.1***	***15.6***	***37.6***

Source: Frontier Energy

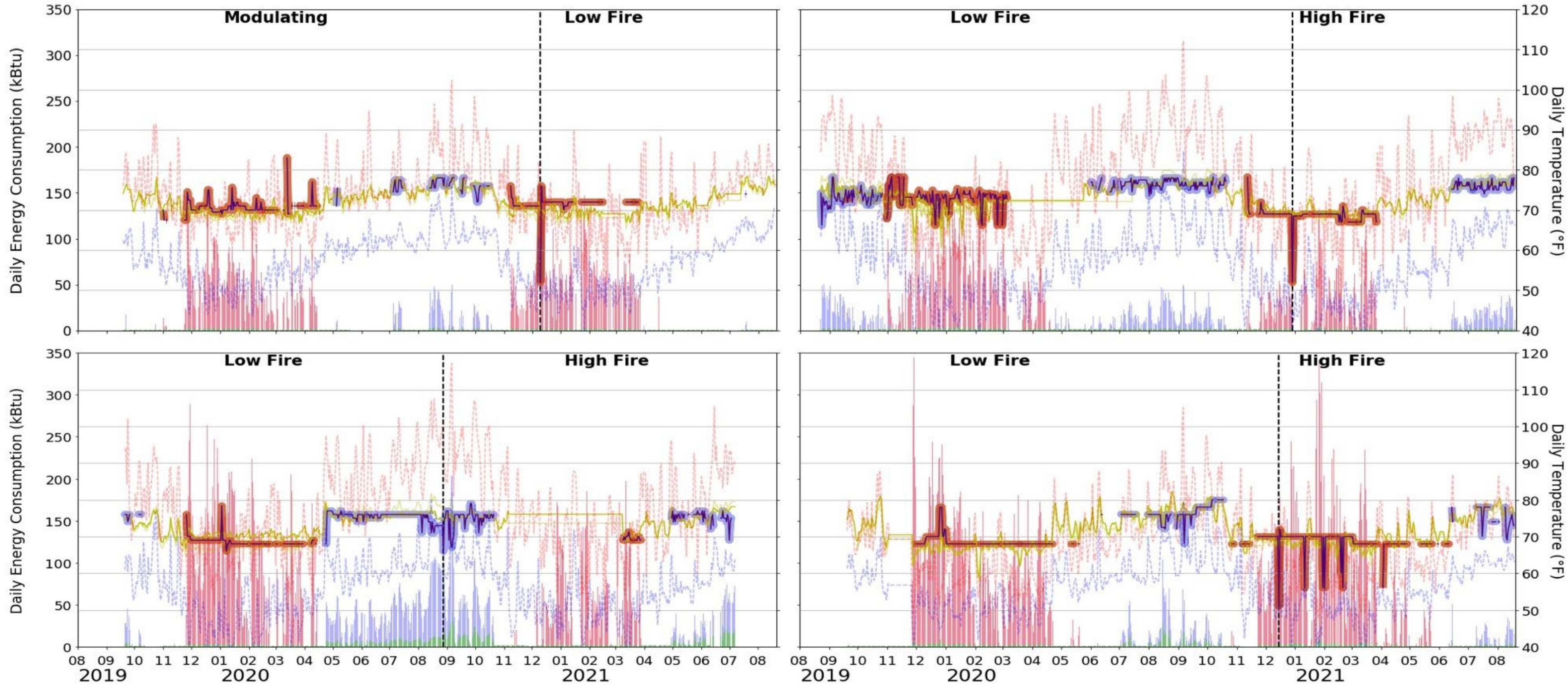
Gas meters and watt-hour transducers were used to measure energy consumption. Data was collected at 15-second intervals, and aggregated to hourly, daily, and monthly intervals. Figure 29 and Figure 30 illustrate the total daily energy consumed, including consumption of the furnace or “Gas Energy”, blower motor or “Indoor Electric Energy”), and condensing unit or “Outdoor Electric Energy”. All energy units are kBtu/day and electric data units were converted to site kBtu. Also shown are the daily minimum and maximum outdoor air temperatures (OAT), temperature setpoint, and zone temperatures measured at the thermostat and at a remote temperature sensor location. The setpoint line on the chart indicates whether the unit is in cooling or heating mode and the setpoint temperature relevant to the mode.

Figure 29: Daily Energy Use, Outdoor Temperature (min and max), and Setpoint - LFS



Source: Frontier Energy

Figure 30: Daily Energy Use, Outdoor Temperature (min and max), and Setpoint



Clockwise from top left: CMJ, CVC, RPS, NRB

Source: Frontier Energy

Table 27 shows the monthly average energy consumption per day for each site. The data is reported as average per day, to normalize for months of different length. Again, in this table, values representing operation at HI fire are in bold text and values representing operation at LO fire are in italicized text. The averages shown are based on only the non-zero values.

Table 26: Monthly Cooling and Heating Energy Consumption in Average kBtu-in/day

MONTH	CMJ - COOL	CMJ - HEAT	CVC - COOL	CVC - HEAT	LFS - COOL	LFS - HEAT	NRB - COOL	NRB - HEAT	RPS - COOL	RPS - HEAT
AUG ‘19	-	-	*40.2*	-	*36.0*	-	-	-	-	-
SEP ‘19	**2.3**	-	*21.2*	*0.1*	*22.7*	*0.0*	*20.1*	-	*0.2*	-
OCT ‘19	**0.2**	-	*8.2*	*0.9*	*10.8*	*0.0*	*1.6*	-	-	-
NOV ‘19	**0.0**	**15.8**	*1.0*	*22.4*	*0.7*	*16.4*	-	*29.5*	-	*31.1*
DEC ‘19	-	**60.5**	*0.2*	*64.6*	-	*66.6*	-	*139.7*	-	*162.2*
JAN ‘20	-	**56.2**	*0.0*	*76.5*	-	*55.6*	*0.0*	*113.1*	-	*104.3*
FEB ‘20	-	**39.6**	*0.2*	*58.4*	-	*44.2*	-	*76.7*	-	*49.5*
MAR ‘20	-	**23.2**	-	*24.9*	-	*37.4*	-	*65.9*	-	*81.2*
APR ‘20	-	**11.5**	*1.2*	*16.1*	*3.0*	*18.8*	*8.7*	*16.6*	-	*49.1*
MAY ‘20	**0.6**	-	*2.3*	-	*5.8*	-	*26.7*	-	-	*2.7*
JUN ‘20	-	-	*3.5*	-	*6.3*	-	*30.5*	-	*0.0*	*0.1*
JUL '20	**6.6**	-	*13.3*	-	*13.9*	-	*49.3*	-	*8.9*	-
AUG '20	**15.9**	-	*21.4*	-	*30.4*	-	*58.4* **5.4**	- -	*23.4*	-
SEP '20	**7.3**	-	*15.2*	-	*20.6*	-	**44.1**	-	*15.4*	-
OCT '20	**5.2**	-	*7.2*	-	*12.3*	*0.4*	**30.6**	-	*5.7*	*1.0*
NOV ‘20	-	**25.6**	*0.1*	*8.5*	*1.7*	*34.6*	-	**1.2**	-	*22.5*
DEC '20	- -	**13.7** *34.9*	- -	*26.2* -	*0.0* -	*54.3* -	**0.1**	**40.7**	- -	*30.8* **66.8**
JAN '21	-	*56.9*	-	**39.7**	-	**61.7**	**0.0**	**70.9**	-	**142.6**
FEB ‘21	-	*46.8*	-	**34.5**	-	**56.0**	-	**37.3**	-	**99.9**
MAR ‘21	*0.1*	*39.0*	-	**38.9**	-	**49.7**	-	**58.5**	-	**96.7**
APR ‘21	-	*1.2*	-	**0.9**	**1.7**	**12.5**	**0.3**	-	**0.4**	**26.0**
MAY ‘21	-	-	-	**0.1**	**2.2**	**1.4**	**10.3**	-	-	**8.0**
JUN ‘21	-	-	**6.2**	-	**10.5**	-	**26.9**	-	**1.9**	**0.1**
JUL '21	*0.5*	-	**16.7**	-	**20.4**	-	**12.8**	-	**7.9**	-
AUG '21	-	-	**12.5**	-	**19.5**	-	-	-	**7.0**	-
Low AVG	**0.3**	**35.7**	**9.0**	**29.9**	**12.6**	**29.9**	**24.4**	**73.6**	**8.9**	**48.6**
High AVG	**4.8**	**30.8**	**11.8**	**22.8**	**10.9**	**36.3**	**14.5**	**41.7**	**4.3**	**62.9**

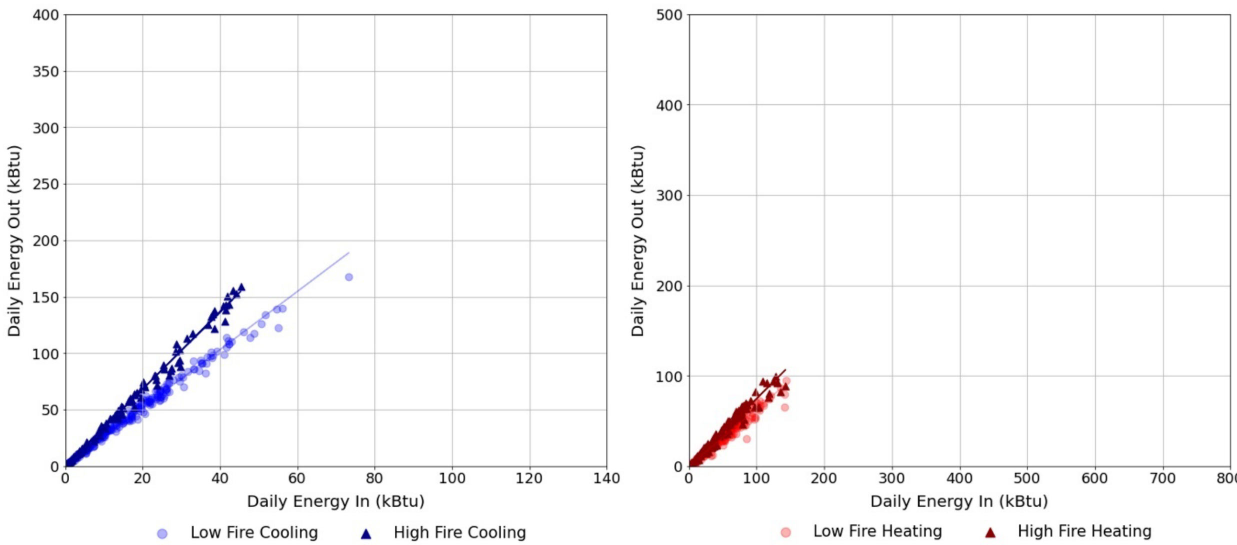
Source: Frontier Energy

Efficiency

Efficiency is expressed as kBtu of useful energy delivered for cooling or heating divided by kBtu of energy consumed, either electricity and/or gas. This can be seen in the scatter charts of energy delivered vs. energy consumed shown in Figure 31 and Figure 32. The slope of the trendline is the efficiency of the heating system (including gas and electric) or coefficient of performance (or COP) of the cooling cycle of the system (including indoor and outdoor units). Table 28 and Figure 33 compare these slopes for each site and shows how the slopes or efficiencies compare between HI and LO fire.

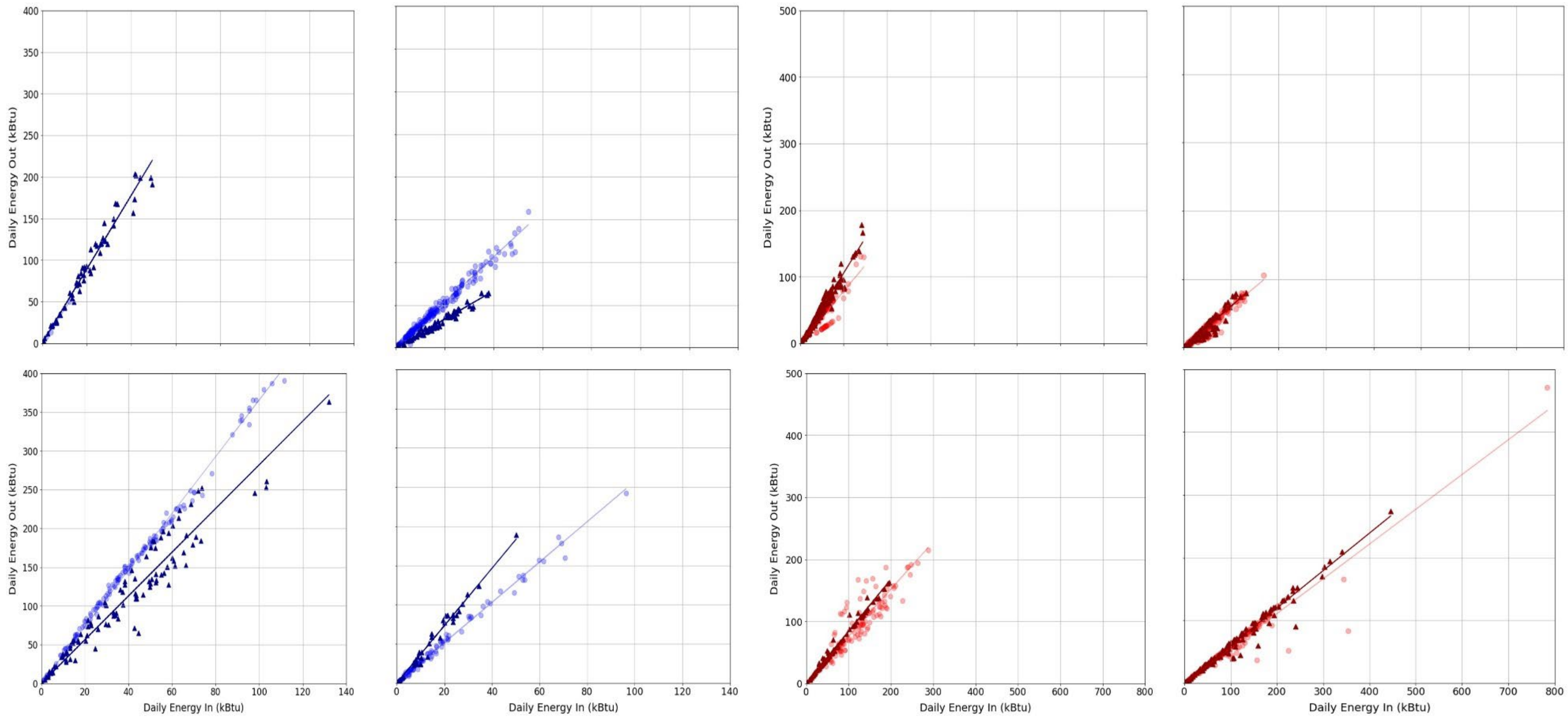
As expected, cooling energy delivered was greater than energy consumed, while heating energy delivered was less than energy consumed. For all sites, the heating efficiency was higher for HI fire, which reflected the higher rated efficiency for HI fire than LO fire, that is 97.5 percent and 96.15 percent, respectively. For cooling, the rated efficiency was slightly higher at LO fire. Measurements varied, however, and some sites had higher efficiency at HI and others at LO fire. On average, HI fire efficiencies were slightly higher, consistent with the rated values.

Figure 31: Cooling and Heating Energy Consumption vs. Energy Delivered - LFS



Source: Frontier Energy

Figure 32: Cooling and Heating Energy Consumption vs. Energy Delivered



Clockwise from top left: CMJ, CVC, RPS, NRB

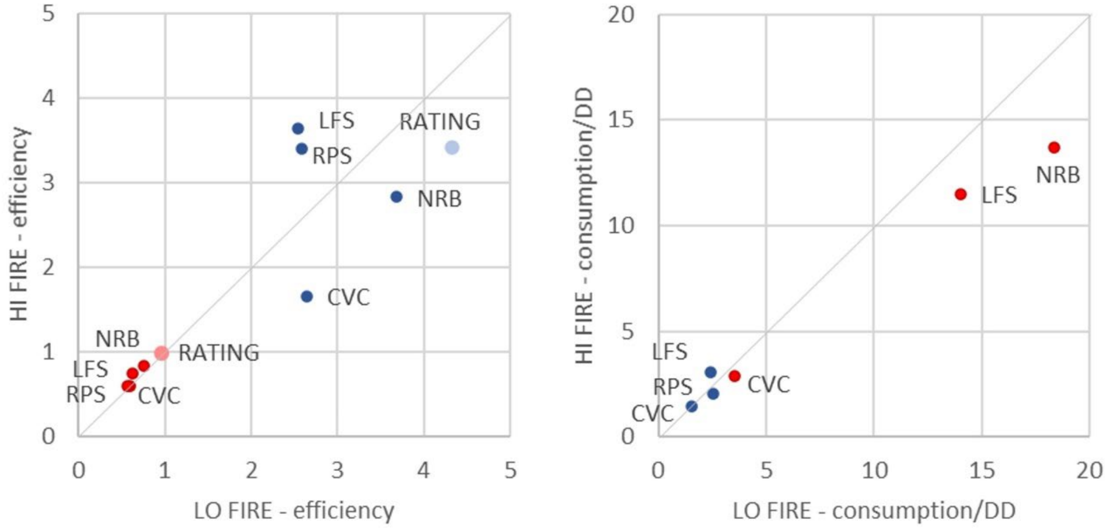
Source: Frontier Energy

Table 27: Summary of Efficiencies - Output/Consumption and Consumption/DD

		kBtu-out / kBtu-in – Heating - HI	kBtu-out / kBtu-in – Heating -LO	HI/LO	kBtu-out / kBtu-in – Cooling -HI	kBtu-out / kBtu-in – Cooling -LO	HI/LO		kBtu-in/ DD – Heating - HI	kBtu-in/ DD – Heating - LO	HI/LO	kBtu-in/ DD – Cooling - HI	kBtu-in/ DD – Cooling - LO	HI/LO
CMJ		*1.06*	*0.78*	*1.36*	*4.45*	*3.35*	*1.33*		*12*	*9*	*1.28*	*2.4*	*0.7*	*3.20*
CVC		0.60	0.59	1.02	1.66	2.64	0.63		3	4	0.82	1.4	1.5	0.92
LFS		0.74	0.63	1.17	3.41	2.58	1.32		11	14	0.82	3.1	2.4	1.28
NRB		0.84	0.76	1.11	2.83	3.68	0.77		14	18	0.75	*5.9*	*5.8*	*1.02*
RPS		0.60	0.57	1.05	3.65	2.54	1.44		*36*	*22*	*1.62*	2.1	2.6	0.80
AVG*		**0.70**	**0.64**	**1.09**	**2.89**	**2.86**	**1.01**		**9**	**12**	**0.78**	**2.2**	**2.2**	**1.01**
RATING		**0.975**	**0.962**	**1.01**	**3.42**	**4.33**	**0.79**							

Source: Frontier Energy

Figure 33: Efficiency and Consumption/DD During HI and LO Fire



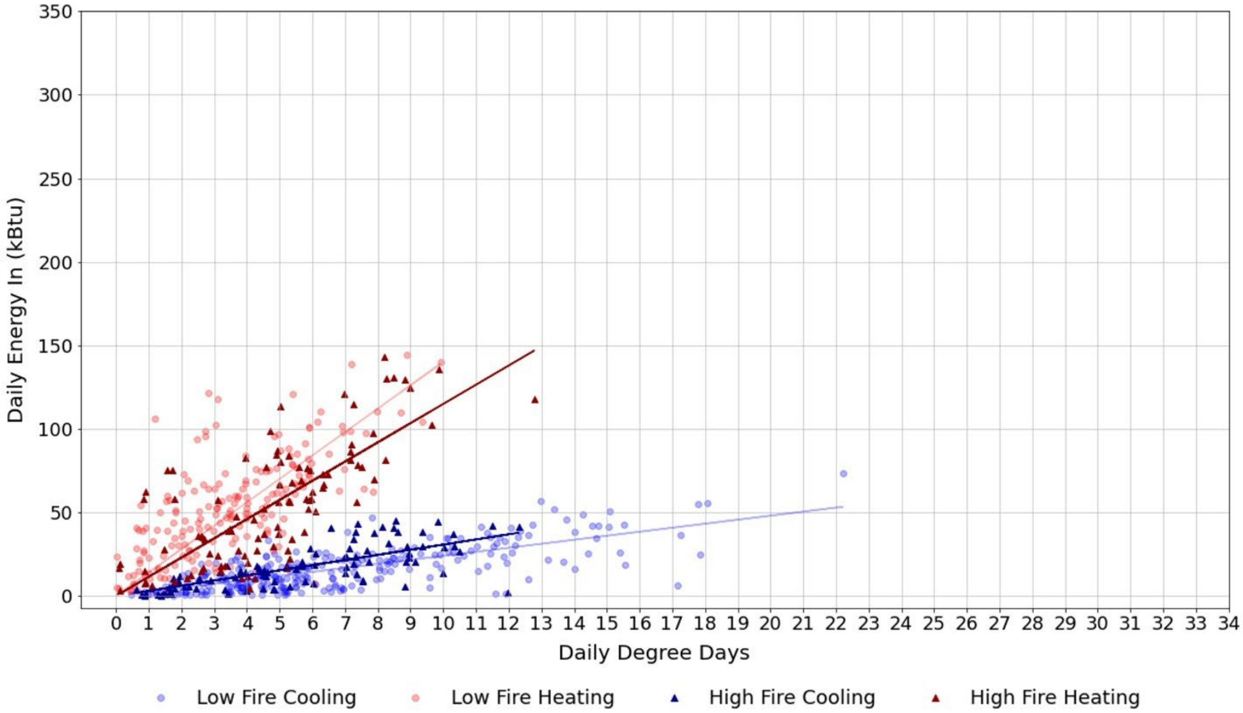
Source: Frontier Energy

Energy per Degree Day

Figure 34 and Figure 35 show a somewhat different way of looking at efficiency. They show the total average energy consumption per day for cooling and for heating versus the CDD and HDD per day, respectively, from the different sites. The slope of the trendline is the energy used per degree day. It should be noted that in this case a smaller number is better. Table 28 and Figure 33 compare these slopes for each site and shows how the slopes (energy used per degree day) compare between HI and LO fire.

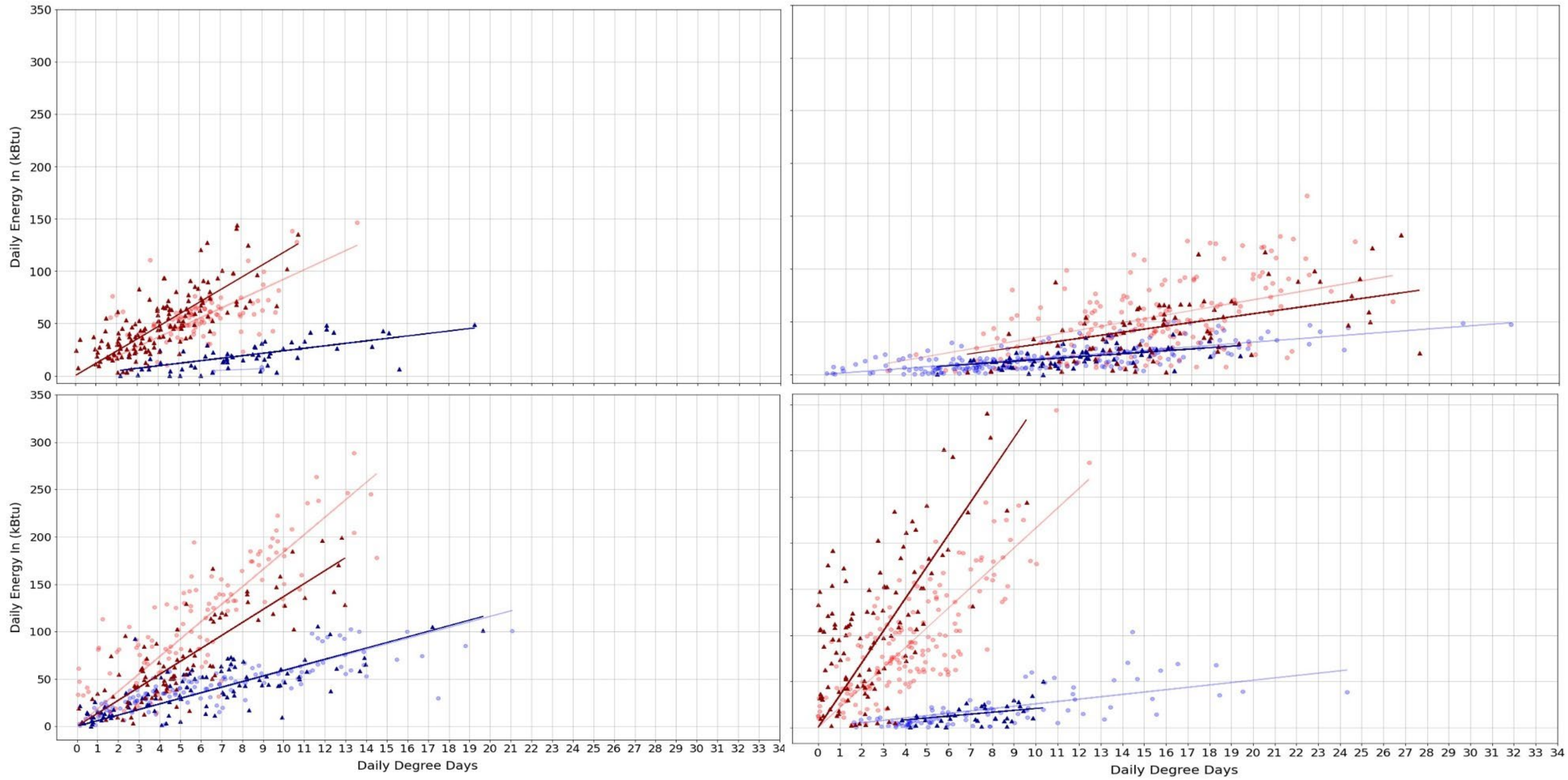
This view is consistent with the previous view of efficiency: for all sites, heating energy consumption was higher for LO fire than HI fire. For cooling, again, the results varied by site, and on average, consumption was very slightly higher for HI than LO.

Figure 34: Daily Cooling and Heating Energy Consumed vs. CDD and HDD - LFS



Source: Frontier Energy

Figure 35: Daily Cooling and Heating Energy Consumed vs. CDD and HDD



Clockwise from top left: CMJ, CVC, RPS, NRB

Source: Frontier Energy

Human Factors and Survey Questionnaires

The project team conducted surveys asking about how the system was operated, the occupants' objectives, and their impressions of the system. An example survey questionnaire is provided in Appendix B.

Table 29 presents the survey responses to the question: "*How often did your household feel uncomfortably {hot/cold} in each of the following rooms, and if so, how much of a problem was it?*". The summary at the end of the table indicates the average number of rooms per home that experienced discomfort (sometimes or often), and the average number of rooms in which discomfort was reported to be a problem. For heating, there were no problems whatsoever with the new system, either at HI or LO fire, while the homes had an average of 0.75 rooms with comfort problems with the prior system. Similarly, the number of rooms experiencing some discomfort was lowest with the new system at LO fire. For cooling, there were an average of 0.75 rooms per home with comfort problems at LO capacity and 0.4 at HI capacity, but this is much reduced from the average of 2.0 rooms per home that experienced problems with the prior system. Again, the number of rooms experiencing discomfort were lowest with the new system at LO fire. These results indicate that low-capacity systems do not have to come with a comfort penalty and can even provide better comfort.

Table 28: Summary of Discomfort and Comfort Problems

○=*Sometimes, but it's not a problem* ☐=*Often, but it's not a problem*

●=*Sometimes, and it's a problem* ■=*Often, and it's a problem*

	PRIOR - Heat ('18-'19)	PRIOR - Cool ('18)	LO FIRE - Heat ('19-'20)	LO FIRE - Cool ('20)	HI FIRE - Heat ('20-'21)	HI FIRE - Cool ('21)
CMJ						
LivRm						
Kitchen						
FamRm						
Bed-lg						
Bed-sm						
Other						
CVC						
LivRm	○	●	○	○		○
Kitchen	○	●				●
FamRm	○	●	○	○		○
Bed-lg	●	●		○		○
Bed-sm	●	●				○
Other						
LFS						
LivRm		☐	○	●	○	○
Kitchen		☐		☐		○
FamRm		☐		●	○	○
Bed-lg		○	○		○	○
Bed-sm		○		○	○	○
Other	☐ Bath				☐ Bath	
NRB						
LivRm	☐	○			○	○
Kitchen	●	○		○	○	○

FamRm		○				○
Bed-lg	□	○		○	○	○
Bed-sm	□	○	○	○	○	○
Other						
RPS						
LivRm	○		○	○	○	○
Kitchen	○	●		○		○
FamRm	○			○		○
Bed-lg	○	●		○	○	○
Bed-sm	○	●	○	●	○	●
Other						
AVERAGE						
Avg Rooms Discomfort	**3.75**	**4.50**	**1.75**	**3.75**	**3.00**	**4.00**
Avg Rooms Problem	**0.75**	**2.00**	**0.00**	**0.75**	**0.00**	**0.40**

Source: Frontier Energy

Table 30 presents the responses to the question: "*Last {winter/summer}, how did you perceive the length of time the system ran each day?*". A response of "3" indicates that the system ran the right amount of time, and anything lower indicates that it ran too long, and anything higher indicates that it ran not long enough. With the prior system, it was common to report that the system ran too long, while one site reported that it ran not long enough. With the low-capacity system in heating mode at either LO or HI fire, most felt that it ran the right amount of time, and one site reported that it ran slightly too long. This result is counterintuitive, since one would expect that the low-capacity system would run much longer than the prior system. One explanation for this response is that the low-capacity system is much quieter, which was also noted by many survey respondents, so the *perceived* runtime is lower. For cooling, most sites felt it ran the right amount of time, and two sits felt it ran too long in cooling mode. For the prior system, two sites felt it ran too long, one felt it ran not long enough, and one felt it ran the right amount of time. These results indicate that occupants did not object to or find troublesome the increased runtime of the low-capacity system.

Table 29: Perception of Runtime

(1=too long, 3=right, 5=not long enough)

	Prior - Heat ('18-'19)	Prior - Cool ('18)	LO FIRE - Heat ('19-'20)	LO FIRE - Cool ('20)	HI FIRE - Heat ('20-'21)	HI FIRE - Cool ('21)
CMJ						3
CVC	1	1	3	3	3	3
LFS	3	2	3	3	3	2
NRB	3	4	3	3	3	3
RPS	2	3	3	2	2	1
AVERAGE	**2.25**	**2.50**	**3.00**	**2.75**	**2.75**	**2.40**

Source: Frontier Energy

Table 31 presents the responses to the question: "*Last {winter/summer}, if you ever came home or woke up to a {cold/hot} house, how long did it usually take to get it to a comfortable temperature?*". In all cases, for both heating and cooling, the perceived recovery time was lower for the low-capacity system than the prior system (except one site that reported an hour to recover with the new system at HI fire). This result is also surprising, since one might expect that a lower capacity system could create problems with excessive recovery time. These results are due to envelope improvements that made the homes more comfortable. Again, these results are reassuring and indicate that the low-capacity system did not create comfort problems.

Table 30: Perception of Recovery Time

	PRIOR - Heat ('18-'19)	PRIOR - Cool ('18)	LO FIRE - Heat ('19-'20)	LO FIRE - Cool ('20)	HI FIRE - Heat ('20-'21)	HI FIRE - Cool ('21)	ΔT in 30 min (LO FIRE) - Heat	ΔT in 30 min (LO FIRE) - Cool
CMJ						30	5.6	3.9
CVC	30	30	15	30	15	20	2.7	2.1
LFS	15	20		15	5	10	2.6	0.8
NRB	30	30		20			3.1	1.8
RPS	30	60	30	20	20	60	4.2	4.0
AVERAGE	**26**	**35**	**23**	**21**	**13**	**30**	**3.6**	**2.5**

Source: Frontier Energy

Temperature Dynamics Tests

Table 31 also presents the results of the temperature dynamic testing, showing that the system at LO fire increased the temperature by an average of 3.6°F in a half hour in heating mode and decreased it by 2.5°F in a half hour in cooling mode. These results seem inconsistent with the overall satisfaction that homeowners expressed with recovery time, and suggest that perception of recovery time may be influenced by a complex combination of factors.

Precooling Investigation

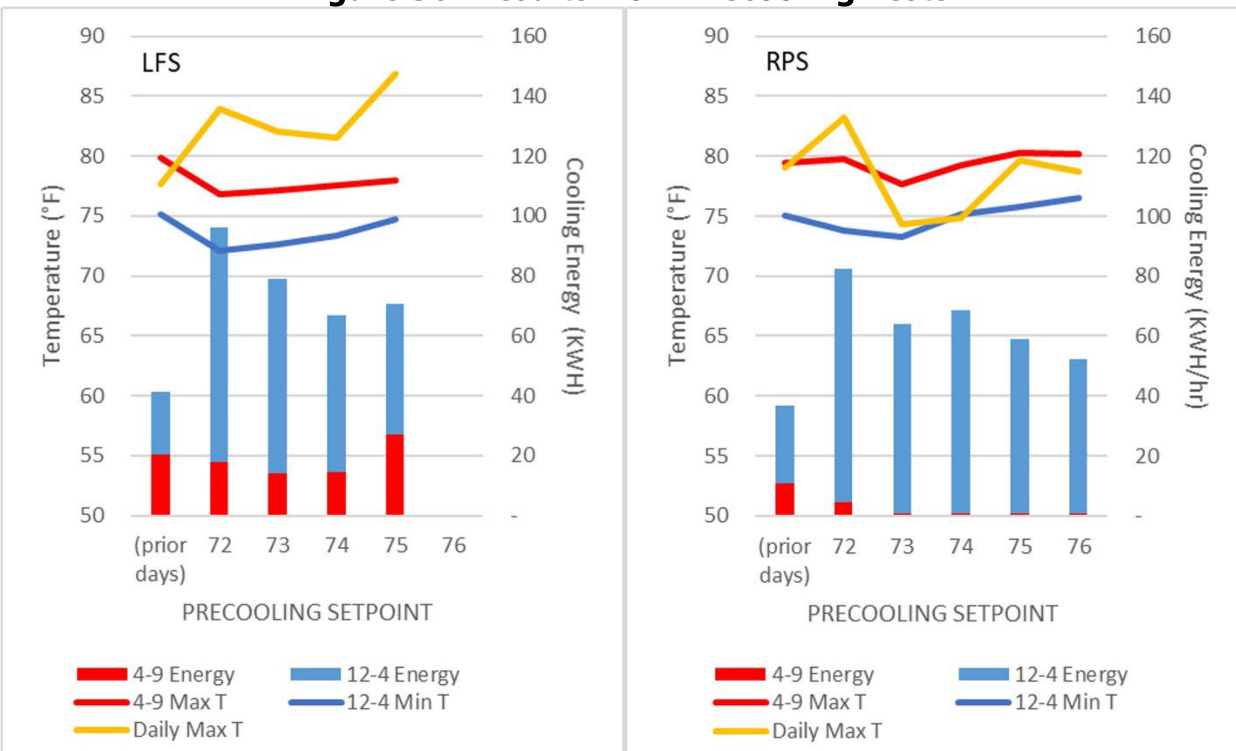
Figure 36 shows the results of the precooling tests. For both the sites studied, the average results are shown for the three days prior to beginning the precooling tests, followed by average results for each precooling setpoint. Each setpoint was tested on 1-2 days. These charts show the daily maximum outdoor temperature, as well as the minimum temperature during the precooling or off-peak period (12 PM-4 PM) and the maximum temperature during the peak period (4 PM-9 PM). The total cooling energy consumed during the 12 PM-4 PM and 4 PM-9 PM periods are also shown.

During the tests, several problems emerged. While the project team was able to readily modify the temperature schedules at each site remotely, the homeowners were enrolled in optimization routines that they were not aware of and the settings did not persist from day to day. Also, this caused other strange behaviors. Prior to the precooling tests, the sites were using less energy than usual for cooling. Also, during the test periods, ambient temperatures were not excessive, and it is likely that little cooling would have been required anyway.

For these reasons, and because a sample of two homes is not enough to draw strong conclusions, these results should be reviewed with caution. Despite these problems the results did indicate that the homes were successful in shifting cooling loads to the period before the peak period. However, both homes consumed more total cooling energy, primarily during the

12 PM-4 PM period, during the precooling tests than in the days prior to the precooling tests. This suggested that limiting precooling to days with high expected on-peak cooling loads would maximize energy and peak savings. Further, higher precooling setpoints resulted in lower overall energy use, although at one site the higher precooling setpoint resulted in more on-peak and total energy use. The current findings indicate that more research should be conducted into optimization of precooling.

Figure 36: Results from Precooling Tests



Source: Frontier Energy

Site Conditions Influencing Project Findings

The main project objective of 30 percent reduction in HVAC energy consumption was evaluated based on the analysis of the utility data and the BEopt energy modeling. Based on interactions with the homeowners, the following feedback was received.

1. The ownership of the CVC site changed during March-April 2020 and the home was unoccupied for a period of time between March and April.
2. The furnace at NRB was not working during Jan-May 2019, resulting in lower-than-expected gas consumption.
3. Electricity use at LFS went from low consumption in summer 2018 to much higher consumption in summer 2019 due to several reasons. The increased use is due to the occupancy increasing from one to two during 2019 and an electric vehicle charger being also installed in mid-2019.
4. At RPS, the electricity usage consistently increased during 2019, partly due to the filtration system of the pool pump needing to be run for longer periods, till about April 2020 when the filter was replaced. Each year post-December, the homeowners

intermittently used electric heaters due to increased occupancy during the winter college break.

These occurrences influenced the energy consumption patterns of different sites.

Stakeholder Feedback

Brief interviews were conducted with an HVAC manufacturer, a contractor who participated in the study, and one homeowner who participated in the study. The main findings are summarized.

Interview with a contractor:

- Lower capacity systems raise a concern that consumers will have to accept a different "type of lifestyle", and success will depend on conveying this expectation. If it results in excessive callbacks because of excessive recovery time, it will not be successful. This is particularly the case for cooling, and less so for heating.
- This has a proper focus on the efficiency of the overall system vs. efficiency of the box.
- Variable speed equipment is the "right way to do this," although the much higher first costs are acknowledged. There could be a niche for people for whom an oversized single-speed system is too expensive.
- Heaters are oversized in California. Manufacturers are starting to come out with systems with lower Btus and higher tons. This is a good trend.
- This could be offered as a prescriptive measure in Title 24.

Interview with a manufacturer:

- This is a good alternative to electrification as a way to reduce carbon emissions. Coupled with other improvements in the home it is a great way to reduce overall energy use.
- Coupled with duct replacements and increased insulation, reducing capacity improves static pressure and helps with electrical draw on the fan motor.
- There are lower-capacity models on the market, but there are fewer options, and increased demand would drive availability of more models.
- The ultra-low NOX requirements are a problem, as they result in more custom designs that are only applicable to a small niche market. This adds to the cost.
- If correct sizing calculations are done, there should be no problem with temperature recovery.

Interview with a homeowner that participated in this project:

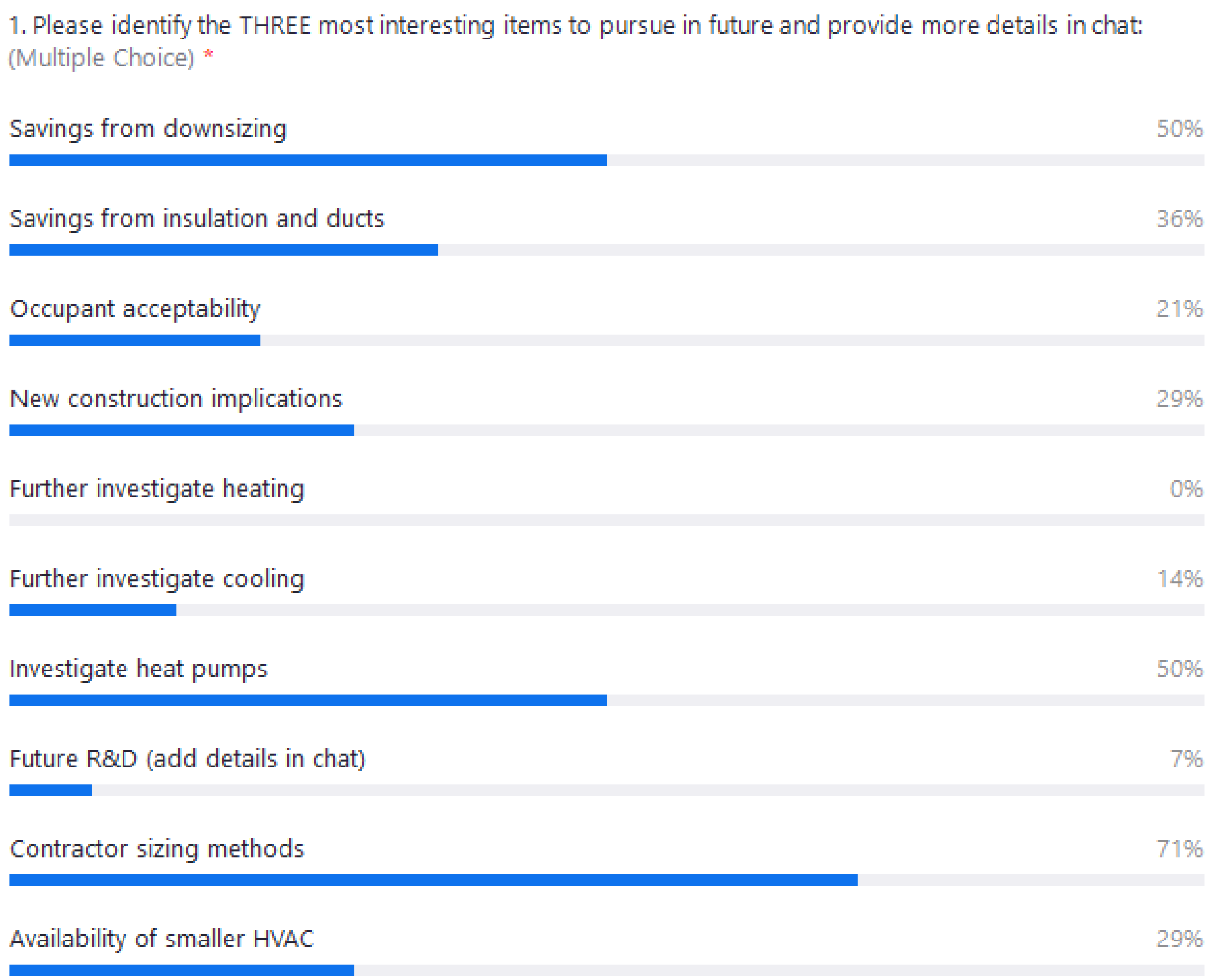
- Expressed satisfaction with the system, particularly at the low-capacity setting. It didn't have the same temperature swings as the high-capacity setting, had less of a problem with draft, and ran quieter.
- Compared with the previous system, both settings were preferable, in terms of health, wellness, and comfort.
- When the new system and new thermostat were installed, the thermostat was not programmed. This resulted in operation that the homeowner didn't understand, which

came to the fore during the precooling tests. The homeowner suggested that contractors should be incentivized to set up thermostats, after having a conversation to determine the occupants' lifestyle, rate tariff, peak and off-peak periods, daily schedules, and temperature preferences.

- Also recommended that contractors should be given incentives to do proper sizing and make sure systems are functioning correctly.

Finally, during a public webinar held on August 25, 2021, the attendees were asked to pick the three most interesting topics from a list provided by the project team for future evaluations and research. Figure 35 shows the poll results from 14 respondents.

Figure 37: Poll Results From August 25 Webinar on Topics for Future Evaluation



Source: Gas Technology Institute

CHAPTER 4: Technology/Knowledge/Market Transfer Activities

The project team plans to make the information available to others as follows:

1. Public – through project final report and fact sheet content made available on the California Energy Commission and GTI websites.
2. Regulatory agencies – through the project final report.

The project results were used to provide information via a public webinar to builders, architects, HVAC professionals, homeowners, program managers, and others regarding retrofit measures and low capacity, high-efficiency HVAC performance. A public webinar was held on August 25, 2021, from 12 PM to 2 PM PDT, with 27 attendees from the following organizations:

1. ADM Associates
2. California Energy Commission
3. Carrier Corp
4. Clayton Homes
5. Cox
6. Gas Technology Institute
7. Robur Corporation
8. Schweitzer & Associates, Inc.
9. Southern California Edison
10. Southern California Gas Company
11. UCI

The team proposes to present the project findings at the following technical conference:

1. Buildings XV Conference, December 5-8, 2022: Topic areas include *HVAC-envelope integration*, which is aligned with the goals of this project. Conference website - https://www.ashrae.org/conferences/topical-conferences/2022-buildings-xv-conference.

The GTI website, at https://www.gti.energy/, will host a sub-website dedicated to sharing the results of this project at https://www.gti.energy/lowcapacityhvac/. In addition to the final report, this website will provide the final project fact sheet for download and copies of any journal articles, presentations, or other publicly available materials that have been developed in support of the project work.

CHAPTER 5: Conclusions/Recommendations

This report summarizes the energy and comfort-related performance of a low-capacity HVAC system that replaced the existing systems in five homes located in Los Angeles and Orange counties, which are characterized by low heating loads and moderate cooling loads. The low-capacity HVAC system was locked in its low-fire stage, that is 26 kBtu/h furnace and 1.5 ton AC, for this first phase of testing and monitoring which spanned from about August 2019 to December 2020. In the second phase from December 2020 through July 2021, the system was locked in its high-fire stage, that is 40 kBtu/h furnace and 2-ton AC. In addition to the HVAC replacement, the five test homes also received modest envelope (attic) and duct upgrades that included additional insulation and air sealing.

The project team collected raw utility data from the test homes before and after the envelope upgrades and HVAC replacement. The utility data was analyzed to estimate the electricity and gas consumption for space cooling and heating, respectively. The cooling and heating energy consumption were normalized by corresponding cooling and heating degree days. A comparison of aggregate heating and cooling energy consumption utility data during winter and summer months, respectively, was done to estimate the energy savings due to the envelope upgrades and low-capacity HVAC system. The results of the aggregate energy comparison showed an average reduction of 33 to 38 percent in gas use for heating and 43 to 48 percent in electricity usage for cooling, when compared to prior years. The LFS site was excluded from the aggregate savings estimates because it showed unexpected increases in both heating and cooling energy use during portions of the low-capacity HVAC period.

To support the utility data analysis, the team performed building energy modeling using BEopt. First, BEopt models were created using the known building characteristics and were calibrated to match the utility data. The inputs to the models were based on site audits, feedback from the homeowners and assumed/default BEopt inputs. The calibrated models showed reasonable agreement with utility data. Discrepancies were observed during periods of anomalous or unusual utility data as well as cases where the model did not accurately capture occupant behavior and/or building characteristics. After the calibration step, the models were used to estimate the energy savings due to the HVAC replacement and envelope upgrades under a common set of weather (TMY data) and operating conditions. The updated modeling results indicated average cooling and heating energy savings of 31 percent and 44 percent, respectively, across the different sites.

The project team monitored the low-capacity HVAC systems over two winter and two summer periods each — in the high-fire and low-fire modes. The variables investigated were the comfort conditions within the homes and HVAC system parameters like cycling, runtime, energy consumption and energy delivered. Site monitoring found that the efficiency of the system at high-fire mode was slightly higher than at low-fire mode, for heating and cooling. It was also found that the average runtime per degree-day was lower in the high-fire mode. For heating, on average, there were the same number of cycles per degree day in the high- and lo-fire mode while for cooling there were more cycles in the high-fire than lo-fire mode. It is important to note, however, that similar site-monitored data was not collected from the prior system, so no direct HVAC performance comparison could be made with the prior system. The experimental design did allow comparison of the operation at high and low fire stages. It should be noted that even in its high-fire mode, the low-capacity HVAC systems operated at lower capacities than the prior systems in the test homes and systems that are typically installed in existing homes. So, while the project team drew comparisons between low and high fire modes, they were both at lower capacities than conventional practice.

The surveys regarding comfort concluded that homeowners were more comfortable with the new low-capacity HVAC system. No comfort problems were reported with the low-capacity system in heating mode in either high-fire or low-fire modes, while the prior systems created problems in an average of 0.75 rooms per home. In cooling mode, there were an average of two rooms per home with comfort problems with the prior system, and only 0.75 rooms with low-fire and 0.40 rooms with high-fire modes of the low-capacity HVAC system. There were also improvements in perceived runtime and in perceived recovery time. Further, lower temperature stratification was observed. Together, these findings indicate that low-capacity systems do not impose a comfort penalty and can even provide better comfort.

CHAPTER 6: Benefits to Ratepayers

To estimate the benefits to California, the project team calculated cumulative energy savings, emission reductions and cost savings for new and retrofit markets. Regarding the retrofit market, based on Construction Industry Research Board (CIRB) [2019], about 6,464,712 single family homes were built in California between 1954 and 2019. For the retrofit market, it was assumed that one out of fifteen single family homes will replace their HVAC systems each year along with attic and duct upgrades. For new construction, starting with the 2019 CIRB projection for single family homes and assuming a 10 percent increment in new homes for subsequent years, the number of new homes to be constructed during 2021-2025 was estimated. For both retrofit and new construction market, a ramping market share of 2 to 10 percent was assumed between 2021 and 2025 for the low-capacity HVAC system and envelope upgrades.

Regarding energy use, according to Energy Information Administration (EIA), about 60 percent of households in California use natural gas for heating. The *2019 California Residential Appliance Saturation Study*, Volume 2: Results estimated the average annual natural gas usage for heating to be 189 therms and average annual electricity use of 1372 kWh for cooling in single family residences.

For the retrofit cases, the project team conservatively assumed a 30 percent reduction in heating and cooling energy consumption, based on the project goal. For new construction, BEopt modeling was done for a single-story, 1,500 square feet home. The baseline new construction home was assumed to be 2019 Title 24 compliant. Thus, the only upgrade that was considered was to replace a 75 kBtu/h, 80 percent AFUE furnace in the baseline new home with a 40 kBtu/h, 97.5 percent AFUE furnace. The 2019 Title 24 requires a SEER 14 AC and a switch to a lower capacity, SEER 16 AC did not yield any appreciable benefits. BEopt modeling of the 2019 Title 24 compliant and upgraded new construction homes were performed in the 16 California climate zones, and the modeling results showed an average of 17 percent reduction in natural gas use for heating.

Table 32 lists the calculation results which show average annual savings of 880,589 therms of natural gas and 6.4 GWh of electricity. Using CO_{2e} emission factors of 5.3 kg/therm and 0.331 kg/kWh, the cumulative CO_{2e} emissions avoided during 2021-2025 is 33,905 metric tons. From a NOx perspective, assuming a difference in emissions based on low NOx (40ng/J) and ultra-low NOx (14 ng/J) furnace specifications, the cumulative NOx emissions avoided due to reduced heating energy use is 12.1 metric tons.

Based on estimates from EIA, the project team assumed that the cost of electricity is 20 cents per kWh and cost of natural gas is $15.31 per 1000 cubic feet (or $1.48/therm). Based on these cost estimates, the average cumulative annual energy cost savings are estimated to be $1,300,418 for natural gas and $1,277,220 for electricity. On a per household basis, the average annual savings for existing homes is estimated to be $166.

Table 31: Estimated Annual Energy Savings and Avoided Emissions

Year	New SF Homes	Retrofit Mkt	Market Share	GWh Saved - New	GWh Saved - Retrofit	GWh Saved - Total	Therms Saved - New	Therms Saved - Retrofit	Therms Saved - Total	CO_{2e} Avoided (kg)	NOx Avoided (kg) (furnace only)
2021	64,619	258,588	2%	-	2.13	2.13	20,538	293,239	293,463	2,259,953	805
2022	71,081	258,588	4%	-	4.26	4.26	45,184	586,479	586,971	4,520,144	1,610
2023	78,189	258,588	6%	-	6.39	6.39	74,554	879,718	880,530	6,780,606	2,416
2024	86,008	258,588	8%	-	8.51	8.51	109,345	1,172,957	1,174,148	9,041,382	3,221
2025	94,608	258,588	10%	-	10.64	10.64	150,350	1,466,197	1,467,833	11,302,516	4,027

Source: Gas Technology Institute

GLOSSARY OR LIST OF ACRONYMS

Term	Definition
AC	Air conditioning
ACH	Air changes per hour
AFUE	Annual fuel utilization efficiency
AHU	Air handler unit
BEopt	Building Energy Optimization
CDD	Cooling degree day
CFM	Cubic feet per minute
CIRB	Construction Industry Research Board
CMJ	Costa Mesa
COP	Coefficient of performance
CVC	Covina
EIA	Energy Information Administration
HDD	Heating degree day
HVAC	Heating, ventilation, and air conditioning
LFS	Lake Forest
NRB	Northridge
OAT	Outdoor air temperature
RH	Relative humidity
RPS	Rancho Palos Verdes
SEER	Seasonal energy efficiency ratio
TMY	Typical meteorological year
WH	Water heater
WHM	Water heater multiplier

REFERENCES

Construction Industry Research Board, CIRB Historical Data 1954-2019, https://cbia.org/cirb-historical-data-1954-2019/ [Accessed July 29, 2021].

Energy Information Administration, Household Energy Use in California, https://www.eia.gov/consumption/residential/reports/2009/state_briefs/pdf/ca.pdf [Accessed July 29, 2021].

Energy Information Administration, California Natural Gas Prices, https://www.eia.gov/dnav/ng/NG_PRI_SUM_DCU_SCA_M.htm [Accessed July 29, 2021].

Energy Information Administration, Average Price of Electricity to Ultimate Customers by End-Use Sector, https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_5_6_a [Accessed July 29, 2021].

APPENDIX A: Cooling and Heating Degree Day Calculation

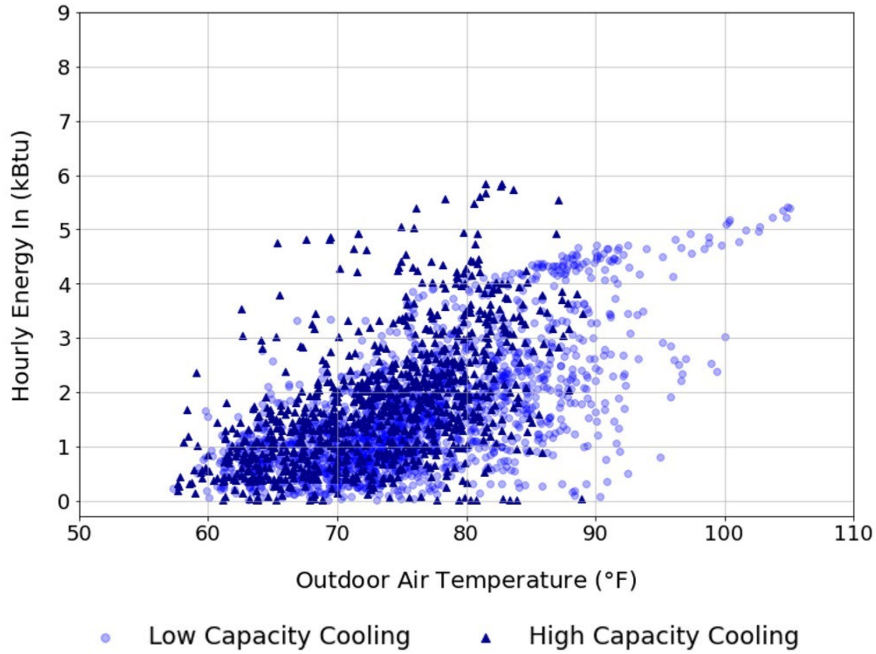
Cooling and Heating degree days (CDD and HDD) are typically used to normalize cooling and heating demand to account for variable weather conditions.

The project team calculated CDD and HDD using weather data from nearby weather stations. The base temperature was established individually for each site, by looking at the hourly cooling or heating energy use vs. the OAT, as seen in Figure A-1 and Figure A-2, and determining the temperature at which the trendline crosses the x-axis. The calculations only considered the points beyond the temperature at which non-zero energy use was first observed.

For each hour, the difference between the average temperature and the base temperature was calculated (minimum of zero), and these hourly values were summed for the day. These degree-days per day were then summed for the month and divided by the number of days in the month to normalize for months of different lengths.

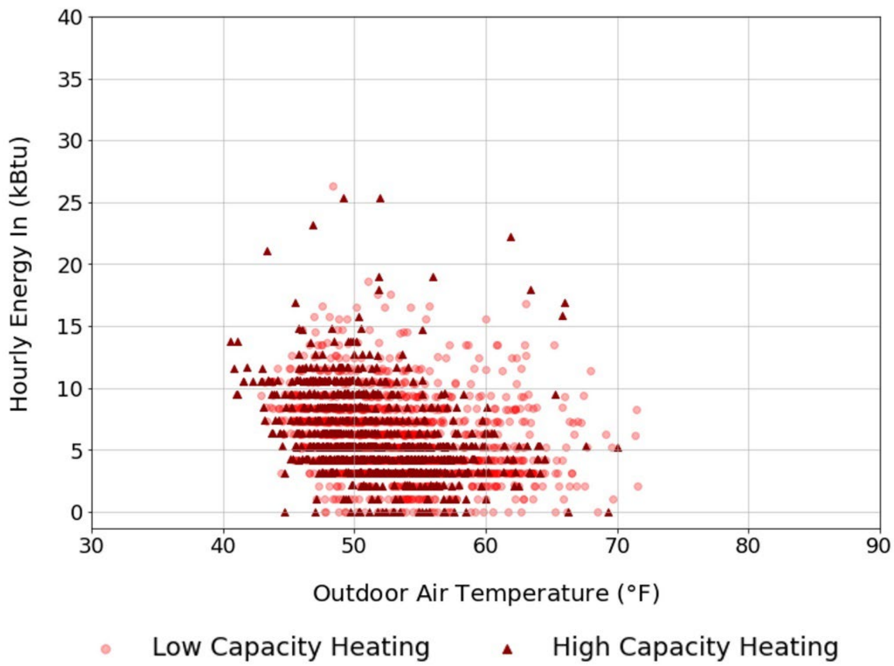
Table A-1 shows the resulting monthly cooling and heating degree-days per day, used throughout the report.

Figure A-1: Hourly Cooling Energy Consumed vs. OAT - LFS



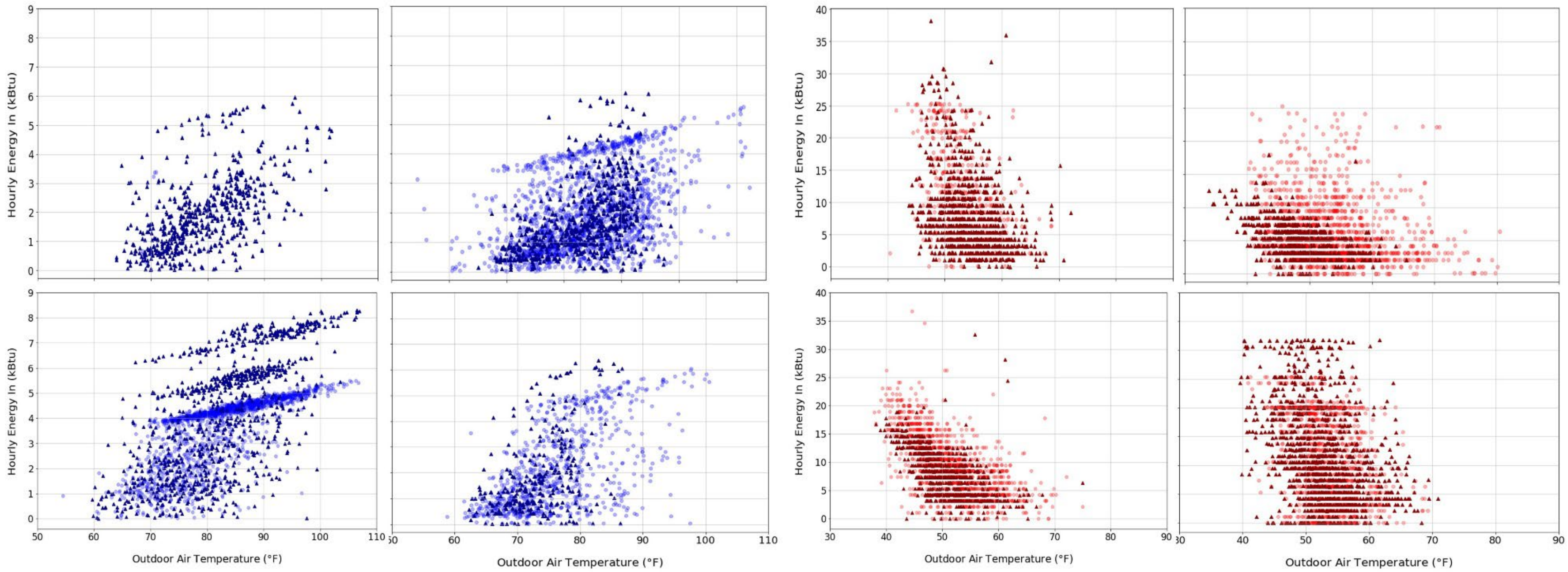
Source: Frontier Energy

Figure A-2: Hourly Heating Energy Consumed vs. OAT - LFS



Source: Frontier Energy

Figure A-3: Hourly Cooling and Heating Energy Consumed vs. OAT



Clockwise from top left: CMJ, CVC, RPS, NRB

Source: Frontier Energy

Table A-1: Monthly Cooling and Heating Degree-Days per Day

	CMJ - CDD	CMJ - HDD	CVC - CDD	CVC - HDD	LFS - CDD	LFS - HDD	NRB - CDD	NRB - HDD	RPS - CDD	RPS - HDD
BASE	**68.2**	**62.2**	**64.9**	**69.6**	**65.3**	**61.4**	**71.9**	**60.1**	**65.0**	**60.1**
AUG ‘19	-	-	11.7	1.1	7.5	-	-	-	-	-
SEP ‘19	6.0	0.0	9.5	2.1	8.8	0.0	6.2	0.1	5.9	0.1
OCT ‘19	4.1	0.4	5.8	5.5	5.9	0.3	3.8	0.7	4.3	1.1
NOV ‘19	1.5	2.5	2.9	11.1	2.3	2.1	2.4	3.8	1.5	3.5
DEC ‘19	0.1	4.6	0.1	17.3	0.4	4.0	0.0	6.4	0.1	5.8
JAN ‘20	0.5	4.5	0.5	16.8	0.9	3.9	0.1	5.1	0.4	5.7
FEB ‘20	1.0	3.5	1.1	14.0	1.6	3.0	0.5	4.9	0.8	4.5
MAR ‘20	0.3	2.3	0.4	15.4	0.6	1.8	0.2	5.5	0.2	4.0
APR ‘20	1.4	1.1	2.7	10.9	2.4	0.8	2.5	2.1	1.3	1.8
MAY ‘20	2.9	0.0	5.3	4.4	5.0	0.0	3.9	0.1	3.0	0.0
JUN ‘20	3.0	0.0	5.6	3.9	4.9	0.0	4.0	0.0	3.9	0.0
JUL '20	3.5	0.0	9.6	2.1	5.6	0.0	7.3	0.0	4.7	0.0
AUG '20	6.5	0.0	14.1	0.9	9.1	0.0	10.4	0.0	8.3	0.0
SEP '20	6.3	0.0	12.2	1.9	8.9	0.0	9.0	0.0	7.4	0.0
OCT '20	4.4	0.3	8.0	3.8	6.7	0.2	5.5	0.3	6.0	0.0
NOV ‘20	1.0	3.5	2.4	12.3	1.6	3.0	1.5	3.2	1.3	2.3
DEC '20	0.6	5.7	1.0	15.7	1.0	5.2	0.5	4.1	0.9	3.0
JAN '21	0.8	6.2	1.1	16.0	1.3	5.6	1.0	4.8	1.6	2.6
FEB ‘21	0.3	4.9	0.5	14.4	0.7	4.3	0.3	3.3	0.6	1.3
MAR ‘21	0.5	5.6	1.1	15.3	0.8	4.9	0.7	5.3	0.7	2.6
APR ‘21	1.1	1.9	2.8	9.6	1.6	1.5	2.2	1.4	1.4	2.2
MAY ‘21	0.7	0.3	2.8	7.2	1.6	0.2	1.6	0.5	1.2	0.4
JUN ‘21	2.2	0.0	8.1	2.7	3.9	0.0	5.4	0.0	4.3	0.0
JUL '21	5.3	0.0	11.6	0.9	8.2	0.0	8.1	0.0	6.5	0.0

Source: Frontier Energy

APPENDIX B: Survey Questionnaire

1. **To start, please tell us about your home as it is RIGHT NOW…**

   (Please write in your answers next to each question):

Are you currently located in your home right now?	*YES / NO*
What is the time and date right now?	____________*am/pm*
	______/_____/ 2020
How many people are in your home right now?	___________________
Approximately what temperature do you think it is **outside your home** right now?	_________________*°F*
Approximately what temperature do you think it is **inside your home** right now?	_________________*°F*
Do you expect to use any kind of equipment to heat or cool your home today?	*HEAT/COOL/NONE* (circle one)
If so, what is the current temperature setting (if you have one)?	_________________*°F*

2. **During the following periods on a typical weekday, how many people are in your home in each age category?**

			Young Children (0-5)	*Older Children (6-13)*	*Teens (14-17)*	*Adults (18-60)*	*Seniors (> 60)*
2:00 am	-	8:00 am					
8:00 am	-	2:00 pm					
2:00 pm	-	8:00 pm					
8:00 pm	-	2:00 am					

3. **Which best describes your household's goal for using heating and cooling equipment last winter?** *(Select only the one that is closest)*

   - O *We try to use the equipment as little as possible.*
   - O *We use the equipment as much as we need it to be comfortable.*
   - O *We try to be frugal, but we want to be comfortable too.*

4. **Please tell us how important each of these factors is when your household decides how to stay comfortable throughout the year.** (*On each row, indicate how important each is to your household.*)

	Very important	*Somewhat important*	*Neither important nor unimportant*	*Somewhat unimportant*	*Very unimportant*
Staying nice and comfortable.	O	O	O	O	O
Reducing energy bills.	O	O	O	O	O
Helping to protect the environment, by reducing energy use.	O	O	O	O	O
Avoiding discomfort.	O	O	O	O	O

Avoiding unexpectedly high bills.	O	O	O	O	O
Not having to think about heat/AC.	O	O	O	O	O
Avoiding climate change consequences, by reducing energy use.	O	O	O	O	O

FOR QUESTIONS 5-11, THINK ABOUT LAST WINTER...

5. How often (if ever) did your household use the following types of heating equipment to keep warm and comfortable last winter? *(Please select the best description, for each row)*

	We didn't have this equipment	*We used it just about all winter.*	*We used it quite a bit.*	*We used it only a few days or nights, when really needed.*	*We used it almost never.*	*We used it never.*
Central heating system.	O	O	O	O	O	O
Wall or floor furnace.	O	O	O	O	O	O
Hydronic system with radiators or baseboard heaters.	O	O	O	O	O	O
Electric space heaters.	O	O	O	O	O	O
Other (please specify: ____________________).	O	O	O	O	O	O

6. Last winter, how often did your household feel uncomfortably cold in each of the following rooms, and if so, how much of a problem was it? *(For each, select the answer that most closely describes how you felt)*

	Often, and it WAS a problem.	*Often, but it was NOT a problem.*	*Sometimes, and it WAS a problem.*	*Sometimes, but it was NOT a problem.*	*Never or almost never.*
Living Room	O	O	O	O	O
Kitchen	O	O	O	O	O
Family Room	O	O	O	O	O
Largest Bedroom	O	O	O	O	O
Smallest Bedroom	O	O	O	O	O
Other Important Room (specify) ______________	O	O	O	O	O

7. Last winter, how did you perceive the length of time the system ran each day? *(Select one)*

Ran way too long.		*Ran just the right amount.*		*Didn't run long enough.*
O	O	O	O	O

What is this perception based on? *(Check all that apply)*

☐ *Comfort* ϒ *Energy Efficiency* ϒ *Lifetime of the system*

8. What did your household like MOST about your primary heating system last winter?

____

____

9. **What did your household like LEAST about your primary heating system last winter?** ____________

____

____

10. **Last winter, if you ever came home or woke up to a cold house, how long did it usually take to get it to a comfortable temperature?**
____________________ minutes

11. **How did your household mostly control your heating equipment last winter? Choose which of the following four approaches *best* describes your strategy.** *(Please check only one of the four approaches, and answer the questions that follow.)*

O *We turned heating equipment on or off, or up or down, as needed.*
We typically turned it **ON** *or* **UP** *for the following reasons: (Please check all that apply)*

- ☐ *When we woke up.*
- ☐ *When we returned home.*
- ☐ *When we started to feel uncomfortably cool.*
- ☐ *When we became so uncomfortably cold, we had to turn it on.*
- ☐ *Other (please explain):* ____

We typically turned it **OFF** *or* **DOWN** *for the following reasons: (Please check all that apply)*

- ☐ *When we left home for the day.*
- ☐ *When we went to bed.*
- ☐ *When things warmed up outside and we could do without heating.*
- ☐ *When we started to feel uncomfortably warm.*
- ☐ *As soon as possible to save energy, even though we were still somewhat uncomfortably cool.*
- ☐ *Other (please explain):* ____

O *We used a thermostat to set one temperature, and left it there most of the time.*
What was that temperature, typically? ______________*°F*
Which of the following best describes that temperature?

Comfortable.	*Mostly Comfortable.*	*Balanced.*	*Mostly Energy-Saving.*	*Energy-Saving.*
O	O	O	O	O

O *We used a thermostat to set one temperature for the day, but then manually changed to an* ***energy-saving setting**** *for the night or for when no one was at home.*
What was the typical temperature setting in the ***morning*** as you prepared to leave? ____________*°F*
What was the typical temperature setting when ***no one was home***? ____________*°F*
What was the typical temperature setting during the ***evening***? ____________*°F*
What was the typical temperature setting when people ***slept***? ____________*°F*
How often did you typically switch it to this ***energy saving setting****?* ____*times/week*

○ *We programmed the thermostat so that different temperatures were automatically maintained at different times of the day and night, or used a "smart" thermostat.*

What was the typical temperature setting in the ***morning*** as you prepared to leave? _____________ *°F*

What was the typical temperature setting when ***no one was home***? _____________ *°F*

What was the typical temperature setting during the ***evening***? _____________ *°F*

What was the typical temperature setting when people ***slept***? _____________ *°F*

How confident were you that it was programmed correctly?

Very confident.	*Somewhat confident.*	*Not very confident.*	*Not at all confident.*	*I don't know.*
O	O	O	O	O

****Examples of energy-saving settings include lowering the thermostat's temperature setting, or turning the equipment down or off.***

APPENDIX C: Additional Building Energy Modeling

To isolate the benefits of upgrading the HVAC systems to a high-efficiency, low-capacity system vs. envelope retrofits, the project team performed additional BEopt modeling for the sites CVC, NRB and RPS. The post-retrofit models were split to consider HVAC upgrade only and envelope (attic) upgrades only. The different upgrades that were modeled are listed in Table C-1.

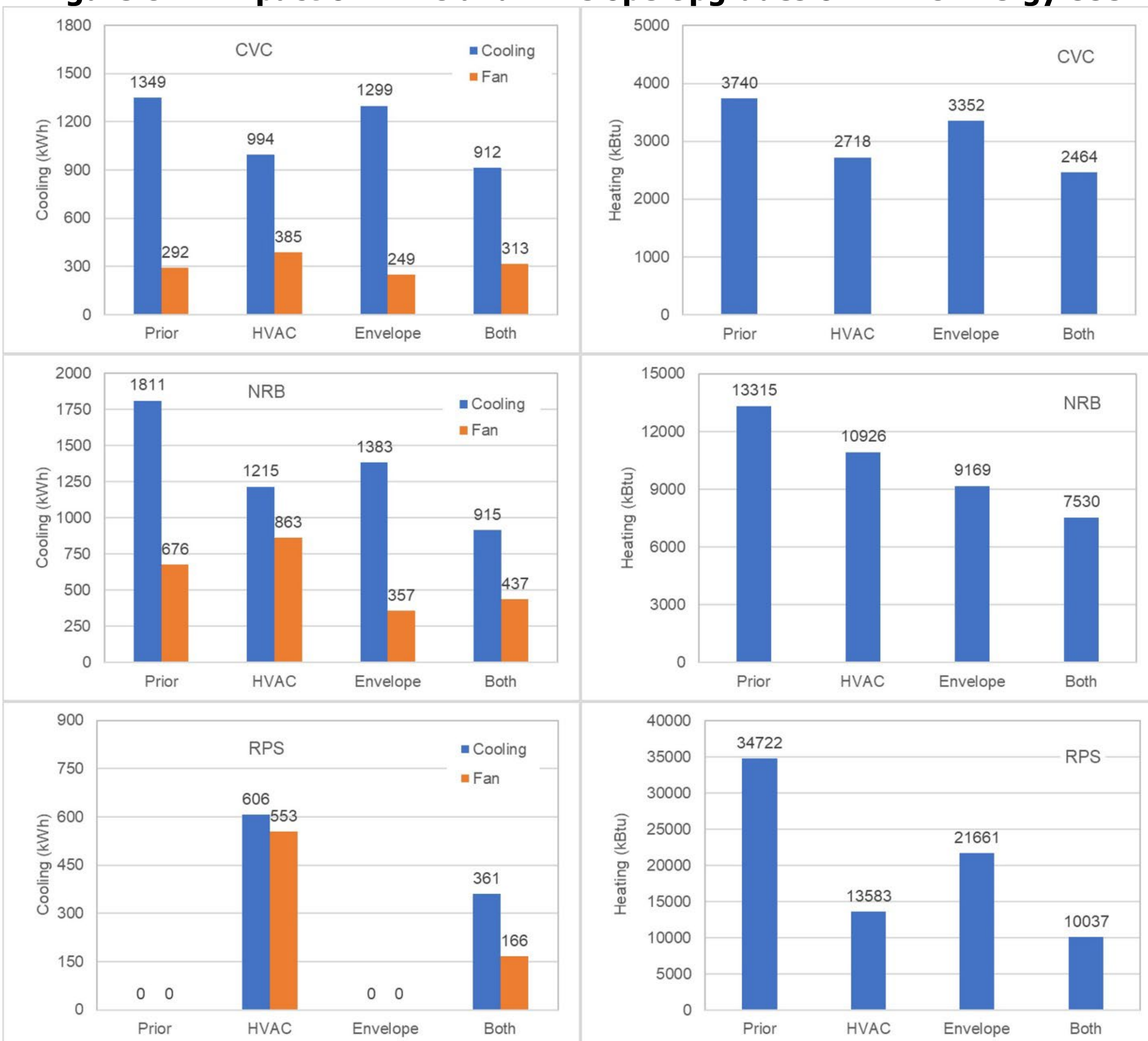
Table C-1: HVAC vs. Envelope upgrades

	CVC	NRB	RPS
Furnace (AFUE / kBtu/h)	81% / 75 → 97.5% / 26	78% / 75 → 97.5% / 26	60% / 125 → 97.5% / 26
AC (SEER / ton)	12 / 4 → 16 / 1.5	10 → 16 / 1.5	N.A. → 16 / 1.5
Attic insulation	R30 → R38	R11 → R38	R32 → R38
Duct insulation	R4 → R8	R8	R4.2 → R8

Source: Gas Technology Institute

Figure C-1 compares the BEopt model calculated HVAC energy consumption with HVAC upgrade, envelope upgrade and the combined HVAC and envelope upgrade, denoted by "Both". At CVC and RPS, the HVAC upgrade reduced the energy consumption more than the envelope upgrades. This is according to expectations since the envelope upgrades were modest for these two sites. Further, at RPS, the HVAC upgrade involved replacing a 60 percent AFUE furnace with one of 97.5 percent AFUE. Conversely, at NRB, the more substantial attic insulation upgrade yielded larger reductions in fan power for cooling and for heating. In general, these results and other observations within the project indicate that an energy efficient envelope is needed to enable and maximize the benefits of high-efficient, low-capacity HVAC systems.

Figure C-1: Impact of HVAC and Envelope Upgrades on HVAC Energy Use



Source: Gas Technology Institute