

Central Valley Research Homes

Variable Capacity Heat Pumps

Evaluation of Refrigerant Charge Effects 2019-2020

ET Project Number: ET14PGE8761_3



Project Managers: Mark Alatorre, Codes & Standards
Kelly Cunningham, Codes & Standards
Pacific Gas and Electric Company

Prepared by: Bruce Wilcox, P.E.

Abram Conant
Lisa Gartland
Proctor Engineering Group, Ltd.

Mike MacFarland
Energy Docs

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ABBREVIATIONS AND ACRONYMS

ACCA	Air Conditioning Contractors of America
AHRI	Air-Conditioning, Heating and Refrigeration Institute
Btu	British thermal unit
CEC	California Energy Commission
CFM	Cubic feet per minute
CT	Current transducer
COP	Coefficient of performance
EER	Energy efficiency ratio
HP	Heat pump
HSPF	Heating seasonal performance factor
HVAC	Heating, ventilating, and air conditioning
kWh	Kilowatt hour
RH	Relative humidity
SEER	Seasonal energy efficiency ratio
SHGC	Solar heat gain coefficient
U	U-factor (thermal transmittance)
VCHP	Variable capacity heat pump

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EXECUTIVE SUMMARY

PROJECT GOALS

The purpose of this project was to evaluate the impact of low refrigerant levels on the cooling and heating seasonal energy performance of variable capacity heat pump (VCHP) systems operating in California homes.

Prior studies have found that incorrect refrigerant levels are common in field installed HVAC systems (Proctor 2002, Pigg 2008) and have documented efficiency impacts associated with incorrect refrigerant levels (Davis 2001, Kruse 2006, Domanski 2014).

The prior research has focused on single speed equipment operating at steady state conditions in a laboratory. This project evaluated the impact of low refrigerant levels on variable speed equipment operating at the range of conditions that occur in single family homes throughout the course of a heating and cooling season.

PROJECT DESCRIPTION

The project was conducted in three of the Central Valley Research Homes (CVRH) in Stockton, CA. The CVRH homes are single family buildings that were converted into laboratory houses in 2012 and have been used to evaluate the energy saving potential of building shell improvements and advanced HVAC technologies through a series of projects supported by the California Energy Commission, Pacific Gas and Electric Company (PG&E), and Southern California Edison (SCE). Occupancy is simulated, and the buildings are intensively monitored and controlled to provide a stable environment for energy evaluation.

Two VCHP systems were installed into each house, and refrigerant levels were varied as the systems were monitored through one cooling season and one heating season. Four refrigerant levels were evaluated: 100%, 80%, 65%, and 50% of the refrigerant amount specified by the manufacturer of the unit. Each VCHP system was tested at each refrigerant level during the cooling and heating seasons. The VCHP systems tested included one 7 zone ductless multi split and one 2 zone ducted multi split at the largest house, and four ducted mini splits at the two smaller houses. The indoor units and all ductwork were located fully inside the conditioned space to eliminate duct losses as a source of uncertainty in evaluating the impact of refrigerant levels on VCHP performance.

Each house was also equipped with a single speed heat pump (used in cooling season) and electric resistance heaters (used in heating season), referred to as Reference cooling and heating systems. The single speed heat pump indoor unit and ductwork was located fully inside the conditioned space. The reference systems served as an unchanging reference for the purpose of normalizing VCHP performance for seasonal effects as VCHP refrigerant levels were varied throughout the project. Each VCHP refrigerant level was tested at a different time during the season, but the reference system operated throughout the entire season with no changes.

The data acquisition and control system (DAS) operated the VCHP and reference systems on a rotating schedule. Each VCHP system was operated for three days at a time, and the reference system was operated for two days. The DAS system rotated between the VCHP and reference systems continuously throughout the cooling and heating seasons.

PROJECT RESULTS

Cooling and heating energy use were analyzed through the following process:

- 1) Monitored reference system daily energy use was modeled at each house as a function of daily average, daily maximum and daily minimum outdoor temperatures, and a seasonal factor representing length of daylight. The resulting models represent the house heating load during heating season, and the cooling load interacted with the reference heat pump cooling efficiency during cooling season.
- 2) Monitored VCHP daily energy use at each refrigerant level was modeled as a function of the calculated reference system daily energy use from step 1 to produce a seasonally normalized representation of VCHP energy use at each refrigerant level. All four refrigerant levels are represented in a single model, with variables representing the change in VCHP energy use relative to reference system energy use at each VCHP refrigerant level.
- 3) The model predicted seasonal VCHP energy use at each refrigerant undercharge level was compared to energy use at correct refrigerant charge to evaluate seasonal energy consumption and efficiency impacts of low refrigerant levels for each VCHP system.

Seasonal cooling energy use and efficiency results for each system and refrigerant level are shown in Table 1. The three houses are identified by their street names: Caleb, Grange, and Mayfair. There are two VCHP systems at each house, identified by nominal capacity at the Grange and Mayfair house and by system type at the Caleb house. The values shown are relative to performance at correct refrigerant charge.

The combined cooling seasonal efficiency results are plotted in Figure 1. On average, these VCHP systems are estimated to lose 10% of their cooling efficiency when refrigerant levels are 25% low and 20% of their cooling efficiency when refrigerant levels are 45% low.

In addition to seasonal cooling efficiency losses, the lowest refrigerant levels caused peak demand on hot summer afternoons to increase by as much as 100% compared to demand with the correct amount of refrigerant.

TABLE 1. IMPACT OF LOW REFRIGERANT CHARGE ON COOLING ENERGY USE AND EFFICIENCY

REFRIGERANT LEVEL	SYSTEM	REFRIGERANT % OF MANUFACTURER SPECIFIED VALUE	NORMALIZED SEASONAL ENERGY USE	NORMALIZED SEASONAL EFFICIENCY
50%	Caleb Ducted VCHP	50%	130%	77%
	Caleb Ductless VCHP	49%	159%	63%
	Grange 0.75 Ton VCHP	50%	131%	76%
	Grange 1 Ton VCHP	51%	152%	66%
	Mayfair 1.5 Ton VCHP*	49%	126%	79%
	Mayfair 2 Ton VCHP	49%	117%	86%
65%	Caleb Ducted VCHP	64%	117%	85%
	Caleb Ductless VCHP	65%	121%	83%
	Grange 0.75 Ton VCHP	65%	117%	85%
	Grange 1 Ton VCHP	66%	110%	91%
	Mayfair 1.5 Ton VCHP*	66%	113%	88%
	Mayfair 2 Ton VCHP	66%	111%	90%
80%	Caleb Ducted VCHP	80%	107%	94%
	Caleb Ductless VCHP	80%	106%	94%
	Grange 0.75 Ton VCHP	80%	110%	91%
	Grange 1 Ton VCHP	80%	112%	90%
	Mayfair 1.5 Ton VCHP	79%	112%	89%
	Mayfair 2 Ton VCHP	80%	109%	91%

* Efficiency impacts are underestimated for these cases. The VCHP did not meet cooling loads at these refrigerant levels.

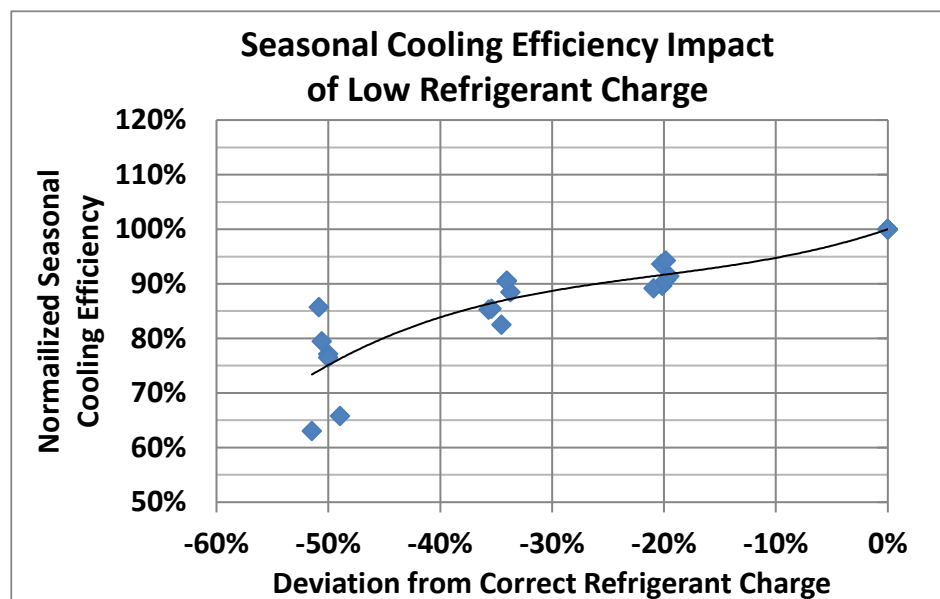
**FIGURE 1. SEASONAL COOLING EFFICIENCY IMPACT OF LOW REFRIGERANT CHARGE**

TABLE 2. IMPACT OF LOW REFRIGERANT CHARGE ON HEATING ENERGY USE AND EFFICIENCY

REFRIGERANT LEVEL	SYSTEM	REFRIGERANT % OF MANUFACTURER SPECIFIED VALUE	NORMALIZED SEASONAL ENERGY USE	NORMALIZED SEASONAL EFFICIENCY
50%	Caleb Ducted VCHP	50%	113%	88%
	Caleb Ductless VCHP	50%	173%	58%
	Grange .75 Ton VCHP	48%	110%	91%
	Grange 1 Ton VCHP	51%	111%	90%
	Mayfair 1.5 Ton VCHP	51%	109%	92%
	Mayfair 2 Ton VCHP	50%	90%	112%
65%*	Caleb Ducted VCHP	65%	90%	111%
	Caleb Ductless VCHP	66%	126%	80%
	Grange .75 Ton VCHP	65%	85%	118%
	Grange 1 Ton VCHP	65%	85%	118%
	Mayfair 1.5 Ton VCHP	65%	90%	111%
	Mayfair 2 Ton VCHP	64%	96%	105%
80%	Caleb Ducted VCHP	80%	103%	97%
	Caleb Ductless VCHP	80%	107%	93%
	Grange .75 Ton VCHP	80%	102%	98%
	Grange 1 Ton VCHP	80%	104%	96%
	Mayfair 1.5 Ton VCHP	81%	101%	99%
	Mayfair 2 Ton VCHP	80%	96%	104%

* The 65% monitoring period was affected by mild weather and very low heating loads. The monitored results are not representative of performance under typical heating conditions.

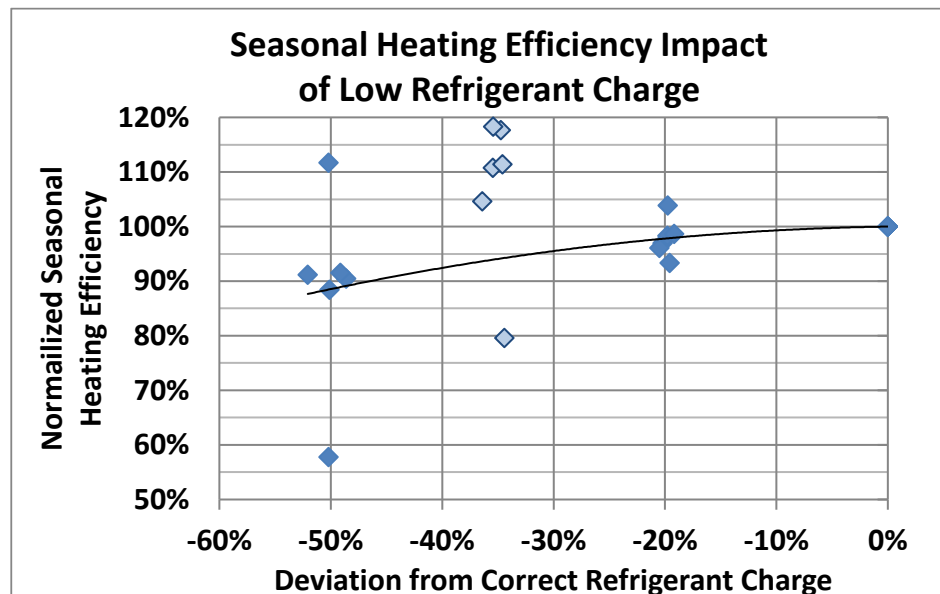


FIGURE 2. SEASONAL HEATING EFFICIENCY IMPACT OF LOW REFRIGERANT CHARGE

Seasonal heating energy use and efficiency results for each system and refrigerant level are shown in Table 2. In general, the heating mode impacts of low refrigerant charge were smaller than the cooling mode impacts.

The 65% refrigerant charge evaluation occurred at the end of heating season and was affected by warm weather and very low heating loads. The monitored results cannot be confidently extrapolated to colder conditions with higher heating loads. The apparent efficiency gains for most systems during the 65% refrigerant charge test are not representative of performance at typical heating conditions.

Heating mode impacts at 50% refrigerant charge ranged from greater than 40% efficiency loss for the Caleb ductless VCHP to 12% improved efficiency for the Mayfair 2 ton VCHP. This indicates that different VCHP systems may respond very differently to incorrect refrigerant levels.

The combined heating seasonal efficiency results are plotted in Figure 2. On average, these VCHP systems are estimated to lose 11% of their heating efficiency when refrigerant levels are 50% low. The study did not find evidence of significant heating efficiency losses when refrigerant levels were greater than 50% of the correct amount, although the 65% refrigerant charge results were inconclusive due to warm weather and very low heating loads during the test period.

These results are representative of the mild winter climate of Stockton, CA. Impacts may differ in colder climate regions, particularly with respect to the potential for increased use of auxiliary heating sources due to reduced heating capacity at low refrigerant levels.

If installed with incorrect refrigerant charge, these VCHP systems are likely to operate at reduced efficiency indefinitely. None of the VCHP systems evaluated provide a method of test for HVAC contractors to verify correct refrigerant charge during commissioning or maintenance visits. This differs from conventional heat pumps which provide test methods such as superheat or subcooling to verify and adjust refrigerant levels. With the exception of one system that malfunctioned and failed to operate on some days when refrigerant charge was 50% low, the VCHP systems did not produce any signal to occupants that there was a problem. With no visibility to HVAC contractors or building occupants that a problem exists, it is unlikely to ever be corrected.

All of the VCHP systems tested were equipped with flare type refrigerant line connections, which are currently typical for residential mini and multi split systems. Flare connections have been documented to be more likely to leak at the time of installation and to develop leaks after installation than brazed or other connection types (Elbel 2018). The monitored results indicate that if a refrigerant leak occurs, VCHP systems are likely to continue operating until refrigerant levels become very low. Five of the six systems tested would lose more than half of their refrigerant before an occupant is likely to notice the problem. In addition to efficiency losses, there are also significant greenhouse gas impacts associated with refrigerant losses, as well as health and safety concerns when leaks occur inside the building.

RECOMMENDATIONS

The study documented substantial cooling mode efficiency losses and the potential for heating mode efficiency losses when the VCHP systems were operated at reduced refrigerant levels. It is recommended that:

- California Title 24 should continue to apply refrigerant charge verification requirements for VCHP systems.
- California Title 24 should apply efficiency loss assumptions to VCHP systems with unverified refrigerant charge. The existing assumption of 10% efficiency loss for central air conditioners and heat pumps is appropriate for VCHP systems because the efficiency losses documented in this study are similar to the losses that would be expected to occur on a standard heat pump system with a thermostatic expansion valve.
- VCHP manufacturers should be encouraged to develop refrigerant charge methods of test that enable equipment installers and maintenance technicians to ensure field installed VCHP systems contain the correct amount of refrigerant. Providing a credit in Title 24 would be one way to encourage this effort. It would be reasonable to assume degraded lifetime efficiency for equipment that lacks methods of test to facilitate ongoing maintenance at correct refrigerant levels. Methods of test must be feasible and practical for residential HVAC contractors. Examples of practical tests include the superheat and subcooling tests that have long been standard for conventional heat pumps. Removing all of the refrigerant and weighing it is not a practical maintenance procedure.
- VCHP manufacturers should be encouraged to develop onboard systems to detect incorrect refrigerant levels or leaks, and alert occupants and the HVAC contractor that there is a problem. Providing a credit in Title 24 would be one way to encourage this effort.
- VCHP manufacturers should be encouraged to adopt refrigerant line connections that are less prone to leakage than flare connections. At present, the installation instructions for nearly all residential mini and multi split type systems specify flare connections.
- Energy efficiency programs that install VCHP systems should include the following components to promote superior technologies and installation practices:
 - Incentivize systems that provide effective refrigerant charge methods of test and/or onboard refrigerant fault detection.
 - Encourage the adoption of refrigerant line connections such as press fittings that are demonstrated to be less prone to leakage than flare connections.
 - Enforce procedures to ensure refrigerant levels are properly adjusted and that all refrigerant line connections are tested and verified to not leak.
 - Include rigorous technician training and certification requirements. At minimum, training should include:
 - Evacuation and charging procedures
 - Refrigerant adjustment to compensate for lineset length
 - Correct installation of refrigerant line connections, including flare connections and options such as press fittings that are demonstrated to be less prone to leakage
 - Refrigerant charge verification methods

INTRODUCTION

Variable Capacity Heat Pump (VCHP) systems are an emerging technology in California and much of North America. A series of studies conducted through the Central Valley Research Homes (CVRH) in Stockton, CA between 2014 and 2019 investigated VCHP system performance in California single family houses. These studies (Wilcox 2016, Wilcox 2018, Wilcox 2019) documented the performance of VCHP systems relative to traditional single speed heat pumps and investigated the opportunities and challenges associated with different types of VCHP equipment and installation approaches.

The prior studies focused on VCHP system performance when the system was carefully installed and commissioned by the research team, or in some cases by the VCHP manufacturer. Installation defects such as incorrect refrigerant charge are known to be prevalent in field installed air conditioner and heat pump systems (Proctor 2002, Pigg 2008). The impact of incorrect refrigerant charge on the efficiency of single speed systems has been studied and is well understood in laboratory environments (Davis 2001, Kruse 2006, Domanski 2014) and is discussed below in the section Refrigerant Charge and Efficiency, but less is known about the effects of incorrect refrigerant charge on variable speed systems.

The 2019-20 CVRH project is an evaluation of the impact of low refrigerant levels on the seasonal heating and cooling energy use of field installed VCHP systems.

BACKGROUND

CENTRAL VALLEY RESEARCH HOMES

The houses used in this study were three of the Central Valley Research Homes (CVRH) houses. The CVRH project is a multi-year effort to test residential energy efficiency measures and technologies in unoccupied, highly instrumented single family homes of different vintages in Stockton, California.

The CVRH project began in 2011 with funding from the California Energy Commission to transform four existing single family residential buildings into fully instrumented laboratory houses for the purpose of evaluating the energy saving potential of building shell retrofits and emerging space conditioning technologies (Wilcox 2018). Starting in the summer of 2015, the PG&E Codes & Standards and Emerging Technology program provided funding to evaluate VCHP system performance in three of the CVRH houses. Starting in 2016, SCE provided funding in coordination with PG&E to continue to evaluate VCHP systems as well as other building shell and HVAC operational topics. (Wilcox 2016, Wilcox 2018, Wilcox 2019)

Project timeline:

- Four homes leased in 2011
- 2012-2013 collected baseline data
- 2013-2014 installed first package of upgrades

- 2014-2015 installed second package of upgrades, including VCHP systems in three homes
- 2015-2016 three VCHP configurations tested in three homes
- 2016-2017 six VCHP configurations tested in three homes
- 2017-2018 five VCHP configurations tested in three homes
- 2018-2019 five VCHP configurations tested in three homes, advanced crawlspace ventilation strategies tested in one home, thermal storage strategies tested in one home

The CVRH houses provide a carefully controlled and consistent real-world laboratory environment to evaluate the energy performance of residential building technologies.

REFRIGERANT CHARGE AND EFFICIENCY

Prior studies have documented high rates of incorrect refrigerant charge in field installed HVAC systems. Testing of 13,000 air conditioner and heat pump units in California found more than half with incorrect refrigerant levels (Proctor 2002). Field evaluations in Wisconsin found similar results (Pigg 2008). Incorrect refrigerant levels may be present at the time of installation, introduced through maintenance practices, or caused by leaks. For split systems, which ship from the factory as separate indoor and outdoor sections that are assembled by the installing HVAC contractor in the field, incorrect refrigerant levels at the time of installation are common.

Mini and multi split VCHP systems are susceptible to the same field assembly and installation defects as single speed split systems, and there are additional reasons for concern:

- Many VCHP systems lack any meaningful method of test to verify correct refrigerant charge. The test methods (superheat, subcooling) used for traditional unitary heat pump systems, including variable speed models, have not been adopted by the manufacturers of variable speed mini and multi split equipment. For most of these systems, the only way to determine if refrigerant levels are correct is to remove all of the refrigerant from the system and weigh it. This is a time consuming and costly procedure that is unlikely to become standard practice for the majority of HVAC contractors installing VCHP systems, leaving the newly installed systems with uncertain refrigerant levels. Once installed, it is unlikely that any future maintenance work would involve removing all of the refrigerant to weigh it, so problems introduced at installation are unlikely to ever be detected or corrected.
- Many mini and multi split VCHP systems are installed using flare connections on the refrigerant lines instead of the brazed connections that are common in traditional split system heat pumps. Anecdotal evidence suggests that approximately 30% of systems with flare connections have a refrigerant leak at one or more connections at the time of installation or develop a leak soon after installation. Limited data from the CVRH 2014 study supports this concern. In 2014 the VCHP systems were installed by an authorized contractor for the brand installed at each house instead of by research team personnel. Of the three systems installed in 2014, one was found to have a refrigerant leak at a flare connection. Research supported by ASHRAE to evaluate refrigerant line connectors for use with flammable refrigerants (Elbel

2018) found 56% of flare connections leaking as originally installed, up to 30% developed leaks during freeze/thaw cycling, and up to 50% developed leaks during vibration testing.

The impact of incorrect refrigerant levels on HVAC system performance has been documented through prior studies (Davis 2001, Kruse 2006, Domanski 2014). In general, systems with fixed refrigerant flow control devices have been found to suffer greater efficiency losses than those with thermostatic expansion valves (TXV). Figure 3 shows results from laboratory tests of single speed air conditioners conducted by PG&E in 2001 (Davis 2001). The results show a rapid loss of efficiency in the Orifice (fixed refrigerant flow control) system as refrigerant levels are reduced below the manufacturer specified refrigerant charge amount, and a less rapid efficiency loss for the TXV system.

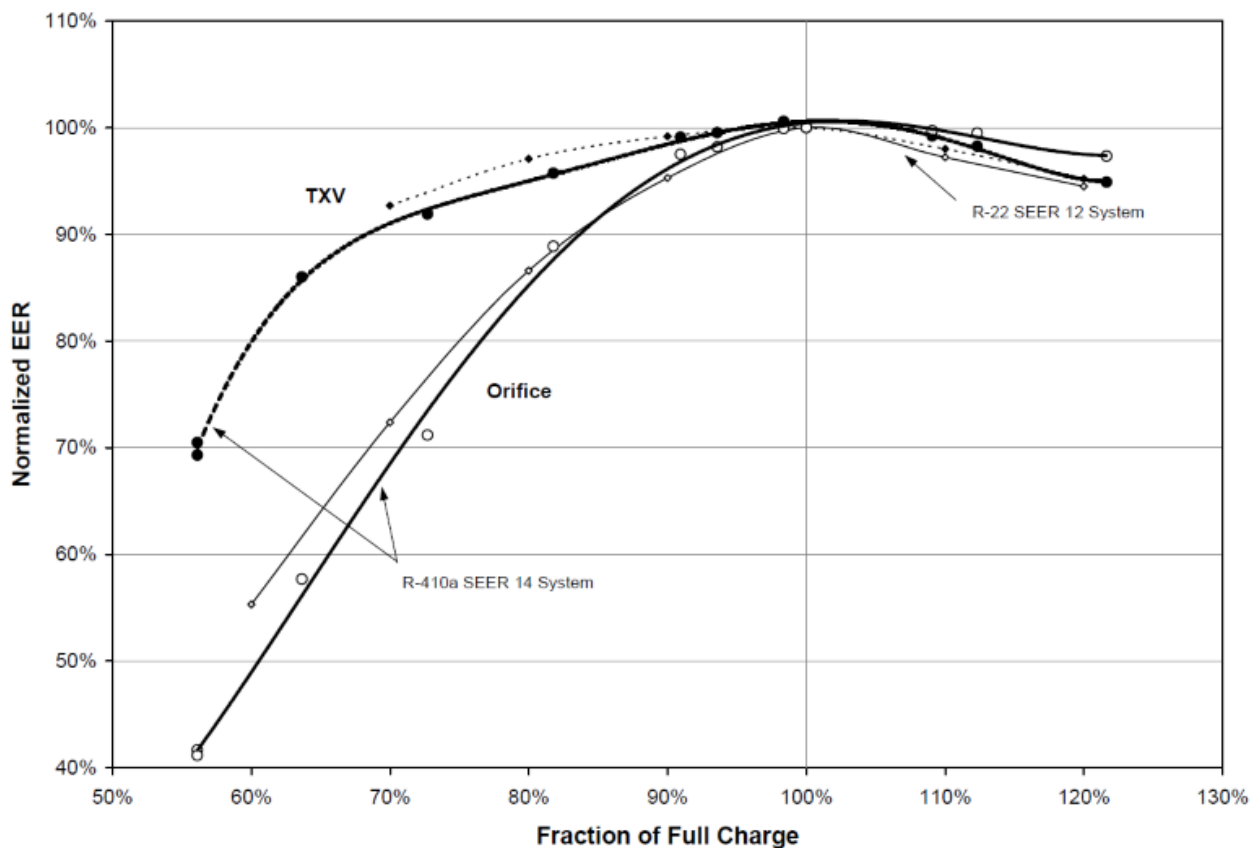


FIGURE 3. REFRIGERANT CHARGE EFFECT ON COOLING EFFICIENCY (SOURCE: DAVIS 2001)

The impact of low refrigerant levels on heat pump heating efficiency has been less studied than the cooling impacts, but some laboratory test results are available (Kruse 2006, Domanski 2014). These results indicate that heating efficiency impacts are less severe than the cooling mode impacts. It is important to note that the laboratory tests focus on steady state efficiency of the vapor compression cycle and there may also be secondary effects such as increased auxiliary heat use caused by reduced heat pump capacity at incorrect refrigerant levels.

Figure 4 displays cooling and heating efficiency laboratory test results published by NIST in 2014. In this figure, "Fault Level" refers to the percent deviation from the correct refrigerant amount, and the numbers in the legend refer to indoor/outdoor temperature in °C in cooling mode, and outdoor temperature in heating mode. In these tests, heating COP losses were less than 10% at 30% undercharge while cooling efficiency losses exceeded 15% at some conditions. Similarly, modest heating efficiency losses are presented in Kruse 2006, which shows 5% to 10% heating efficiency loss at 30% undercharge.

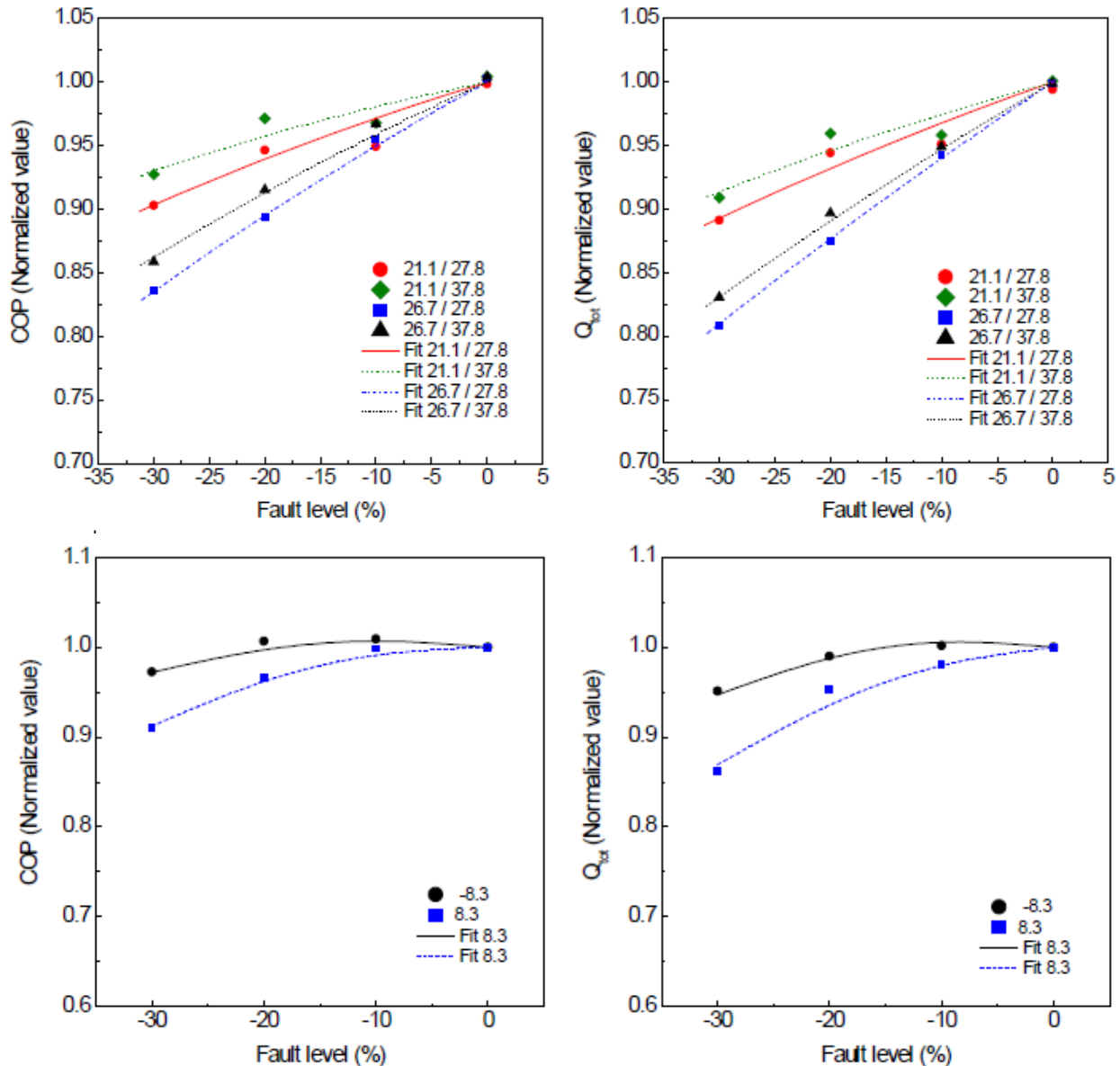


FIGURE 4. REFRIGERANT CHARGE EFFECT ON COOLING (TOP) AND HEATING (BOTTOM) EFFICIENCY (SOURCE: DOMANSKI 2014)

The effect of low refrigerant levels on variable speed systems cannot necessarily be assumed to be similar to single speed systems. VCHP systems can operate over a range of speeds/capacities, and impacts of low refrigerant charge may vary at different speeds. VCHP systems are computer controlled and modulate compressor speed, fan speed, and the EXV refrigerant flow control valve position according to control algorithms that may differ between manufacturers or product lines. Efficiency impacts of low refrigerant levels may vary depending on the control programming.

THE EMERGING TECHNOLOGY

The subject of this study is an emerging HVAC technology: variable capacity heat pumps (VCHP). These systems include mini-split and multi-split systems that are common in Asia and Europe and are increasingly gaining a foothold in the North American market. These systems have the potential to provide more efficient heating and cooling than conventional single-speed heat pumps.

VCHP systems are susceptible to many of the same installation defects that have been documented as problematic in single speed HVAC system installations, including incorrect refrigerant levels. These defects may detract from the delivered energy efficiency of field installed systems. It is not known if VCHP system efficiency losses resulting from installation defects are similar in magnitude to those documented on single speed systems.

ASSESSMENT OBJECTIVES

The objective of this assessment is to monitor the performance of field installed VCHP systems operating at four different refrigerant levels to evaluate cooling and heating seasonal energy efficiency impacts of low refrigerant charge.

TECHNOLOGY EVALUATION

The evaluation plan was as follows:

- 1) Two VCHP systems were tested in each house during one cooling season and one heating season. The amount of refrigerant in the VCHP systems was adjusted to four different levels during each season: 100%, 80%, 65%, and 50% of the manufacturer specified refrigerant amount.
- 2) A single speed heat pump was operated in each house during cooling season, and electric resistance (ER) heaters were operated during heating season. These "Reference" systems remained unchanged throughout the experiment. Their purpose was to provide an unchanging reference to compare VCHP system energy use against in order to develop a seasonally normalized representation of VCHP energy performance at each refrigerant level. This was necessary because the different refrigerant levels were tested at different times during the season, and there are seasonal changes in building heating and cooling loads – e.g. the cooling load on a 90 °F afternoon in June is not necessarily the same as on a 90 °F afternoon in September.
- 3) The energy performance of each VCHP system relative to the reference system was analyzed for each VCHP refrigerant level and projected to a typical year to develop seasonal energy use estimates. These were compared to performance of the VCHP system at correct refrigerant charge to characterize seasonal cooling and heating energy impacts at each reduced refrigerant level.

TEST METHODOLOGY

TEST LOCATIONS

The three houses in this study — referred to as Caleb, Grange, and Mayfair— are located in Stockton, California. Stockton is located in California Climate Zone 12, in the middle part of California's Central Valley. This inland region is characterized by cooler winters and hotter summers than the San Francisco Bay Area to its west. The winter rainy period extends from November to April and is generally fairly mild. Summer high temperatures can exceed 110 °F but average 93 °F in August. Daily lows average 58 °F in August due to a mesoscale sea breeze that cools the area into the 60s °F except when a peak hot spell occurs. A good summary of Climate Zone 12 characteristics can be found in "The Pacific Energy Center's Guide to California Climate Zones." (Pacific Energy Center, 2006).

Each of the homes received energy efficiency upgrades as part of an earlier study (Wilcox 2016). The envelope performance was improved so that it approaches the 2016 California Title 24 requirements for new dwellings.

CALEB

Built in 2005, the four bedroom, 2,076 ft² house on Caleb Circle is the newest and largest of the test houses. It is a two-story rectangular home with a portion of the second story overlapping the garage



FIGURE 5. CALEB TEST HOUSE – FRONT AND SIDE VIEW



FIGURE 6. CALEB TEST HOUSE – REAR VIEW

TABLE 3. CALEB HOUSE CHARACTERISTICS

Floor Area	2,076 ft ²
Year Built	2005
Stories	2
Bedrooms	4
Floor type	Slab on grade
Air Leakage	1,615 CFM50 (5.4 ACH50)
Attic Insulation	R-30 loose fill fiberglass + PolyFoam (3M) PolySet spray foam system under roofing tiles
Attic Ventilation	16.7 ft ² (1 ft ² vent / 66 ft ² ceiling area)
Wall Insulation	R-17
Windows	Vinyl, double-pane, low-E, U 0.35, SHGC 0.30
IAQ Ventilation	ASHRAE 62.2 compliant bath exhaust fan, 64 CFM, 12.1 watts
Whole-house fan	Four whole-house fans installed in ceiling. Total 2,075 CFM and 275 watts (not operated during this study)
Heating Load	21,577 Btu/hr (see Wilcox, 2016)
Cooling Load	25,084 Btu/hr (see Wilcox, 2016)

GRANGE

Built in 1948, the Grange Avenue house is the oldest of the test houses. At 848 ft², it is also the smallest. It is a two-bedroom, single-story rectangular house with slab on grade construction.



FIGURE 7. GRANGE TEST HOUSE

TABLE 4. GRANGE HOUSE CHARACTERISTICS

Floor Area	848 ft ²
Year Built	1948
Stories	1
Bedrooms	2
Floor type	Slab on grade
Air Leakage	438 CFM50 (3.8 ACH50)
Attic Insulation	852 ft ² , R-49 loose fill fiberglass
Attic Ventilation	15.5 ft ² (1 ft ² vent / 55 ft ² ceiling area)
Wall Insulation	R-10 loose fill fiberglass
Windows	78 ft ² , vinyl, double-pane, low-E ² , U 0.30, SHGC 0.25
IAQ Ventilation	ASHRAE 62.2 compliant bath exhaust fan, 39 CFM, 5.5 watts
Whole-house fan	Two whole-house fans installed in ceiling. Total 1213 CFM and 141 watts (not operated during this study)
Heating Load	12,775 Btu/hr (see Wilcox, 2016)
Cooling Load	10,253 Btu/hr (see Wilcox, 2016)

MAYFAIR

The house on West Mayfair in Stockton is the second oldest test home. This three-bedroom home was built in 1953 and has a floor area of 1,104 square feet. It is a simple one-story rectangular building over a crawlspace.



FIGURE 8. MAYFAIR TEST HOUSE - FRONT



FIGURE 9. MAYFAIR HOUSE – REAR (SHADE STRUCTURE REMOVED BEFORE EXPERIMENTS)

TABLE 5. MAYFAIR HOUSE CHARACTERISTICS

Floor Area	1,104 ft ²
Year Built	1953
Stories	1
Bedrooms	3
Floor type	Crawlspace
Air Leakage	1,248 CFM50 (9.3 ACH50)
Attic Insulation	1,104 ft ² , R-49 loose fill fiberglass
Attic Ventilation	20 ft ² (1 ft ² vent / 55 ft ² ceiling area)
Wall Insulation	R-13 loose fill fiberglass
Crawlspace Efficiency	Uninsulated, plastic membrane on floor, code-minimum vent area
Windows	197 ft ² , vinyl, double-pane, low-E ² , U 0.30, SHGC 0.25
IAQ Ventilation	ASHRAE 62.2 compliant bath exhaust fan located in the crawlspace, exhausts 91 CFM from the crawlspace while drawing 41 CFM from the house to the crawlspace, 4.7 watts
Whole-house fan	Three whole-house fans installed in ceiling. Total 1,638 cfm and 202.5 watts (not operated during this study)
Heating Load	15,583 Btu/hr (see Wilcox, 2016)
Cooling Load	16,175 Btu/hr (see Wilcox, 2016)

TEST PERIOD

Systems were commissioned during the spring of 2019 and were monitored through the spring of 2020. Cooling season data was monitored from June 2019 through September 2019. Heating system data was monitored from December 2019 through March 2020.

HVAC SYSTEMS

Table 6 lists the type and basic specifications for the VCHP systems installed in each house for the 2019-20 study.

TABLE 6. 2019-20 VCHP SYSTEMS

HOUSE	SYSTEM	DESCRIPTION	EQUIPMENT SPECIFICATIONS	
Caleb	Ducted VCHP	Multi split with two ducted indoor units (1 st floor 1.5 ton, 2 nd floor 2 ton, 1 branch box)	SEER: 14.7 EER: 8.7 Rated Cooling Capacity, Btu/hr: 42,000* HSPF: 9.3 Rated Heating Capacity, Btu/hr: 47,000* Mfg. Specified Refrigerant Weight, lbs: 9	
	Ductless VCHP	Multi split with seven ductless indoor units (3 wall mount and 4 ceiling mount, rated at 7,000 BTU/h cooling and 8,100 BTU/h heating each, 3 branch boxes)	SEER: 17.0 EER: 9.25 Rated Cooling Capacity, Btu/hr: 49,000* HSPF: 9.8 Rated Heating Capacity, Btu/hr: 56,700* Mfg. Specified Refrigerant Weight, lbs: 11.85	
Grange	1 Ton VCHP ⁺	Mini-split with ducted indoor unit	SEER: 29.3 EER: 15.2 Rated Cooling Capacity, Btu/hr: 12,000 HSPF: 14.0 Rated Heating Capacity, Btu/hr: 18,000 Mfg. Specified Refrigerant Weight, lbs: 2.88	
	0.75 Ton VCHP ⁺	Mini-split with ducted indoor unit	SEER: 33.0 EER: 18.0 Rated Cooling Capacity, Btu/hr: 9,000 HSPF: 14.2 Rated Heating Capacity, Btu/hr: 12,000 Mfg. Specified Refrigerant Weight, lbs: 2.88	
Mayfair	1.5 Ton VCHP ⁺	Mini-split with ducted indoor unit	SEER: 21.0 EER: 12.5 Nominal/Maximum Cooling Capacity: 17,200/21,000 HSPF: 12.0 Nominal/Maximum Heating Capacity: 20,300/30,000 Mfg. Specified Refrigerant Weight, lbs: 3.44	
	2 Ton VCHP	Mini-split with ducted indoor unit	SEER: 19.6 EER: 11.7 Nominal/Maximum Cooling Capacity: 24,000/24,000 HSPF: 10.8 Nominal/Maximum Heating Capacity: 26,000/28,000 Mfg. Specified Refrigerant Weight, lbs: 7.69	

* Heating and cooling capacities based on total indoor head capacities for each system. The outdoor unit is AHRI listed at 48,000 BTU/h in cooling mode and 54,000 BTU/h in heating mode for both the ducted and ductless combinations.

+ These units do not have AHRI ratings in combination with a ducted indoor unit. It is assumed that ratings are equal to an AHRI listed ductless combination using the same outdoor section and an indoor section with the same rated capacity.

Central heat pump systems are commonly installed with supplemental electric resistance heaters to provide additional heat when the compressor is unable to meet the load, or during defrost cycles when the heat pump operates in cooling mode to defrost the outdoor coil. Mini and multi split systems are not typically equipped with supplemental electric resistance heat. In these systems, the indoor fan is shut off or operated at very low speed during defrost to avoid blowing cold air into the house. None of the tested VCHP systems were equipped with electric resistance heat.

Table 7 displays VCHP system sizing relative to the ACCA Manual J predicted cooling and heating loads. The Caleb multi split systems and the Mayfair 2 ton VCHP are oversized relative to the Manual J loads, and the Grange 0.75 ton VCHP is undersized relative to the cooling load according to Manual J. The Caleb units are oversized due to the need for the outdoor unit to support seven ductless heads, with minimum capacity of 7,000 BTU/h per head in the commercially available equipment. The Mayfair 2 ton and Grange 0.75 ton VCHP were previously used in a sizing experiment and included in this study to represent a range of HVAC system sizing in the project results.

TABLE 7. 2019-20 VCHP SYSTEM SIZING RELATIVE TO ACCA MANUAL J

HOUSE	MODE	SYSTEM	MANUAL J LOAD (BTU/H)	MANUFACTURER PUBLISHED CAPACITY AT STOCKTON, CA DESIGN CONDITION (BTU/H)	EQUIPMENT CAPACITY / MANUAL J DESIGN LOAD (%)	MAXIMUM MONITORED* HOURLY LOAD (BTU/H)	EQUIPMENT CAPACITY / MONITORED LOAD (%)
Caleb	Cooling	Ducted VCHP	18,715	38,977	208%	16,745	233%
		Ductless VCHP	18,715	44,867	240%	16,745	268%
	Heating	Ducted VCHP	21,710	45,543	210%	9,711	469%
		Ductless VCHP	21,710	53,826	248%	9,711	554%
Grange	Cooling	0.75 Ton VCHP	9,330	8,320	89%	8,243	101%
		1 Ton VCHP	9,330	11,080	119%	8,243	134%
	Heating	0.75 Ton VCHP	12,135	16,760	138%	5,609	299%
		1 Ton VCHP	12,135	18,729	154%	5,609	334%
Mayfair	Cooling	1.5 Ton VCHP	12,973	16,000	123%	10,405	154%
		2 Ton VCHP	12,973	22,736	175%	10,405	219%
	Heating	1.5 Ton VCHP	13,198	17,360	132%	7,176	242%
		2 Ton VCHP	13,198	18,373	139%	7,176	256%

* This is the maximum load that occurred in any hour during monitoring, and is based on the monitored electric resistance heat in heating mode, and calculated from the reference HP measured airflow, monitored temperature drop between the return and supply plenums, and monitored condensate volume in cooling mode.

Table 7 also shows the maximum monitored heating and cooling loads in each house. The Manual J estimated loads exceed the monitored loads in all cases. All of the units are capable of meeting the monitored loads in the houses. The four VCHP systems tested at the Caleb and Mayfair houses are oversized by more than 50% relative to

the monitored cooling loads. All six VCHP systems are oversized by 200% or more relative to the monitored heating loads.

The very large amount of oversizing relative to the heating loads is an important consideration in interpreting the results of this experiment. The units never operated at full capacity in heating mode. Efficiency impacts of low refrigerant levels may be different at higher heating capacity operation than was monitored during this study.

Table 8 shows specifications for the single speed heat pumps for the Caleb, Grange and Mayfair houses. These units were verified to have correct refrigerant levels prior to cooling season, and the refrigerant levels remained unchanged throughout the experiment to serve as an unchanging reference for use in developing a seasonally normalized model of VCHP performance at each refrigerant level.

TABLE 8. CALEB, GRANGE AND MAYFAIR REFERENCE HP SYSTEMS

HOUSE	DESCRIPTION	EQUIPMENT SPECIFICATIONS	
Caleb	2.5 Ton split system heat pump	SEER:	14
		EER:	12
		Rated Cooling Capacity:	28,000
		HSPF:	8.2
		Rated Heating Capacity:	27,800
Grange	2 Ton split system heat pump	SEER:	14.0
		EER:	11.5
		Rated Cooling Capacity:	23,200 Btu/hr
		HSPF:	8.2
		Rated Heating Capacity:	23,200 Btu/hr
Mayfair	2 Ton split system heat pump	SEER:	14.0
		EER:	11.5
		Rated Cooling Capacity:	23,200 Btu/hr
		HSPF:	8.2
		Rated Heating Capacity:	23,200 Btu/hr

In addition to the reference heat pump systems, each house was also equipped with electric resistance heaters in each room. The resistance heaters were individually controlled by the data acquisition system (DAS). During heating season, the electric resistance heaters were used as the unchanging reference heat source. This provides a very consistent heat source with known and unchanging COP of 1.

HVAC SYSTEM CONFIGURATION

CALEB HOUSE

The ducted and ductless VCHP units at Caleb were originally installed and monitored during 2018-19. The same units were used in the 2019-20 refrigerant charge study.

The ductless VCHP system at Caleb was specified based on a California Title 24 (2019) requirement that each room be directly conditioned. To meet this requirement, seven indoor heads are needed to condition each of Caleb's seven rooms. The smallest commercially available ductless indoor heads are rated at 7,000 Btu/hr, which exceeds the cooling and heating loads in any individual room at the

Caleb house. The manufacturer literature specifies a 4 ton outdoor unit for this combination of indoor units.

Two different types of ductless indoor heads were installed: 1) wall-mounted heads in the living room, on the landing, and in the master bedroom, and 2) ceiling-mounted heads in the dining room, and in bedrooms 1, 2 and 3. Examples of the ceiling and wall units at Caleb are shown in Figure 10. Each head was separately controlled by an external thermostat located in an aspirated enclosure suspended in the center of the room being heated. All of the indoor heads were located fully inside conditioned space.



FIGURE 10. DUCTLESS VCHP INDOOR UNITS: CEILING UNIT IN DINING ROOM (LEFT), AND WALL UNIT IN LIVING ROOM (RIGHT)

The ducted VCHP at Caleb used a 4 ton outdoor unit identical to that of the ductless VCHP. The outdoor unit was paired with two low static indoor units of 1.5 tons on the 1st floor and 2 tons on the 2nd floor, yielding a total cooling capacity of 42,000 Btu/hr and heating capacity of 47,000 Btu/hr.

As shown in blue in Figure 11, the ducted VCHP had separate duct systems serving the first and second floor of the house and supplying air to each room on that floor. This system was controlled by thermostats in aspirated enclosures suspended near the center of the living room (first-floor system) and the landing (second-floor system). The indoor units and ducts were located fully inside the conditioned space. Bedroom doors were left open at all times during the study.

The Caleb reference HP system was sized to meet the ACCA Manual J (ACCA 2016) predicted cooling loads at Caleb. This system was equipped with Title 24 (2019) compliant zonal control, with one zone serving the first floor and a second zone serving the second floor. A schematic of the reference system's ductwork is shown in Figure 11 in magenta. The thermostats controlling the reference system were located in aspirated enclosures suspended near the center of the living room and the landing. The reference system air handler and ductwork were fully inside conditioned space.

During winter 2019-20 the reference heat pumps did not operate and the electric resistance heaters were used as the reference heating system. Heaters in each room were controlled individually based on temperatures in aspirated enclosures hanging in the center of each room.

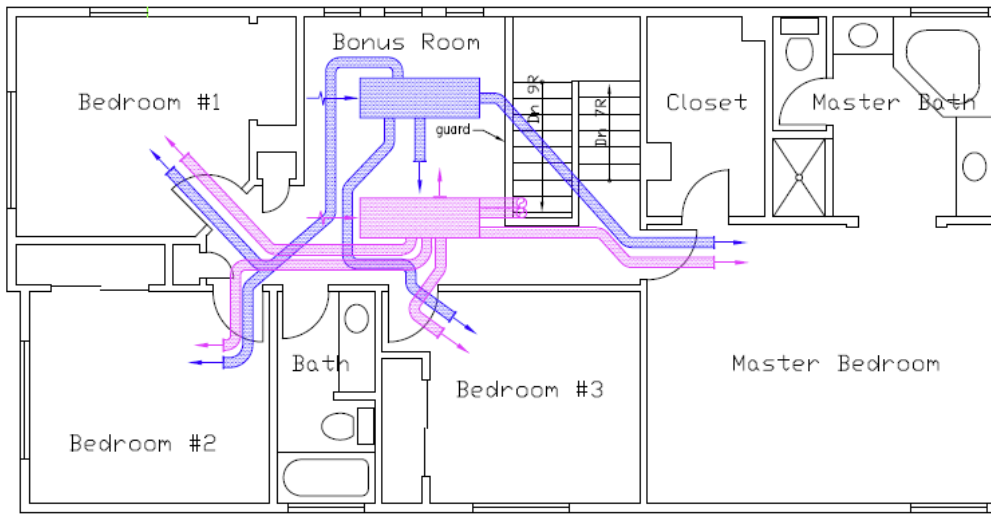


FIG. 5C-CALEB CIRCLE-UPPER FLOOR-1/8"=1'-0" 2017-2018
05/02/18

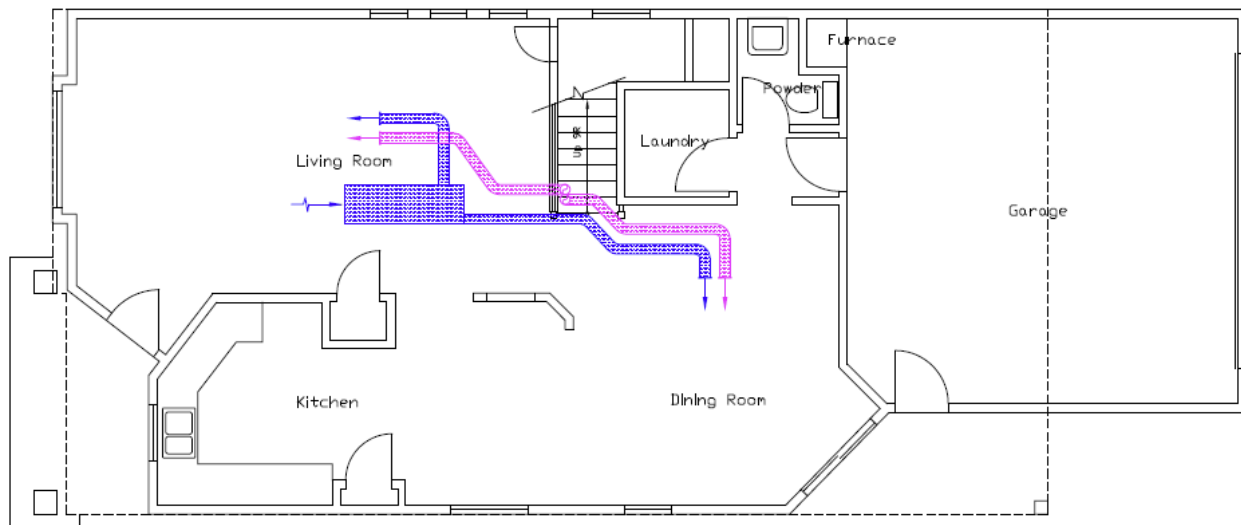


FIG. 4C-CALEB CIRCLE-LOWER FLOOR-1/8"=1'-0" 2017-2018
05/02/18

KEY TO SYSTEM TYPES

	REFERENCE SYSTEM
	DUCTED VCHP

FIGURE 11. CALEB FLOOR PLAN AND DUCTED REFERENCE AND VCHP HVAC SYSTEMS

GRANGE HOUSE

The VCHP units at Grange were originally installed and monitored in 2016 and 2017. The two units are from the same product manufacturer and product line.

The reference HP system was installed in 2018. It is sized approximately a half ton larger than would typically be installed based on the Manual J load calculations because the 2018 project required additional capacity for a thermal storage experiment. The same unit was used for the 2019-20 study. Oversizing does not impact the 2019-20 results since the only purpose of the reference system is to serve as an unchanging reference for use in normalizing VCHP performance at different refrigerant levels.

As shown in Figure 12, the VCHPs and reference HP indoor units were installed into a common supply plenum. The VCHPs were stacked on top of each other in horizontal flow position, and the reference HP indoor unit was installed in an upflow position. Dampers allowed airflow from the active system into the supply plenum, and prevented airflow through the inactive systems.

This common duct installation provided an identical air distribution system for each HVAC unit. All ductwork was located fully within the conditioned space. All HVAC systems were operated as single zone systems controlled by a thermostat located in an aspirated enclosure hanging in the center of the living room.

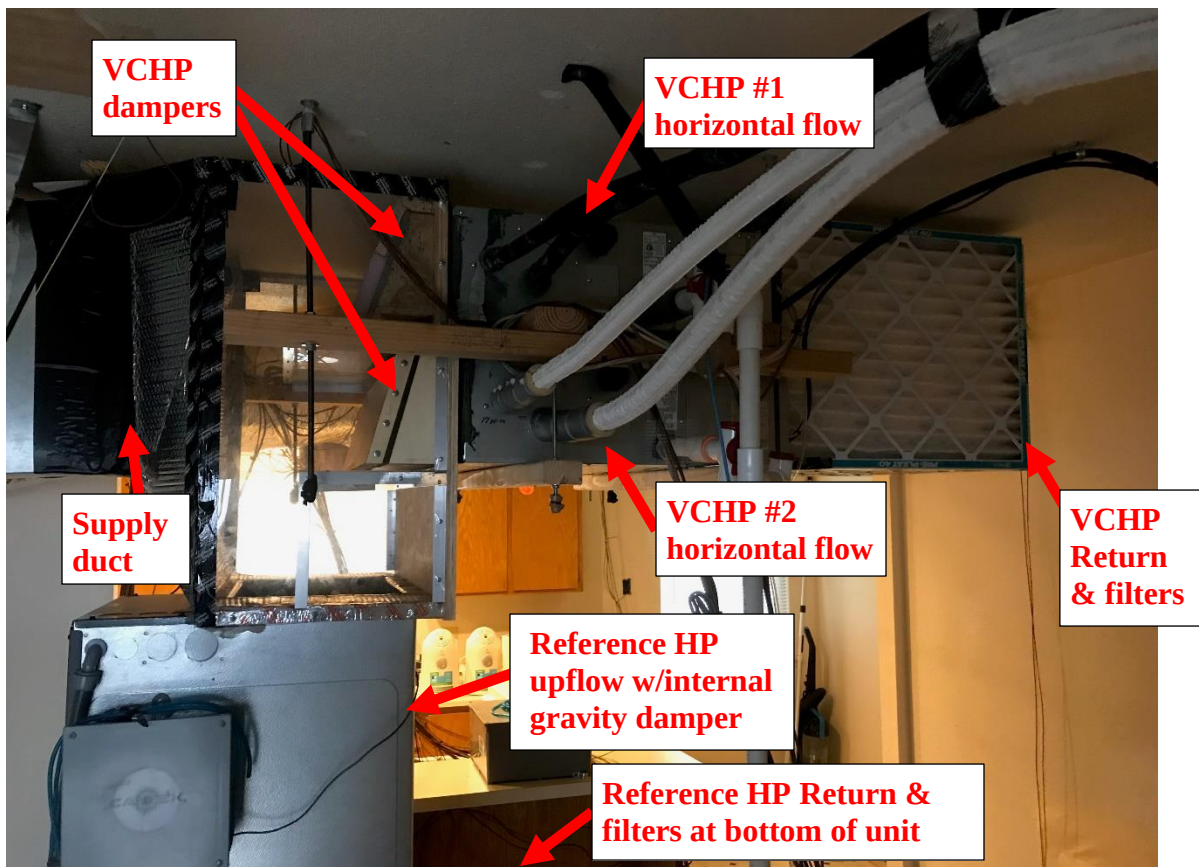


FIGURE 12. GRANGE REFERENCE HP AND VCHP SYSTEM INDOOR UNIT COMMON DUCT INSTALLATION

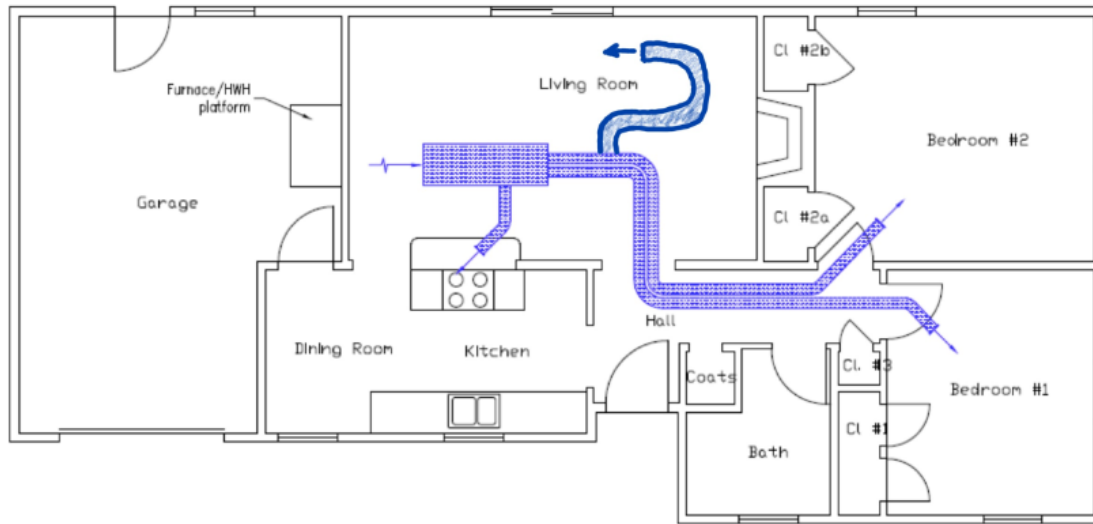


FIGURE 13. GRANGE FLOOR PLAN AND HVAC DISTRIBUTION SYSTEM LAYOUT

During winter 2019-20 the reference heat pumps did not operate and the electric resistance heaters were used as the reference heating system. Heaters in each room were controlled individually based on temperatures in aspirated enclosures hanging in the center of each room.

MAYFAIR HOUSE

The VCHP units at Mayfair were originally installed in 2016 and 2018. The two units are produced by the same manufacturer, but are from different product lines. The reference HP unit was installed in 2018 and is sized to represent a typical installation based on the Manual J predicted loads.

The Mayfair indoor units were installed in the same configuration as at the Grange house (Figure 12), with all three indoor units sharing a common supply system with dampers preventing airflow through the inactive units.

All ductwork was located fully within the conditioned space. All HVAC systems were operated as single zone systems controlled by a thermostat located in an aspirated enclosure hanging in the center of the living room.

During winter 2019-20 the reference heat pumps did not operate and the electric resistance heaters were used as the reference heating system instead. Heaters in each room were controlled individually based on temperatures in aspirated enclosures hanging in the center of each room. The VCHPs had no supplemental strip heat.

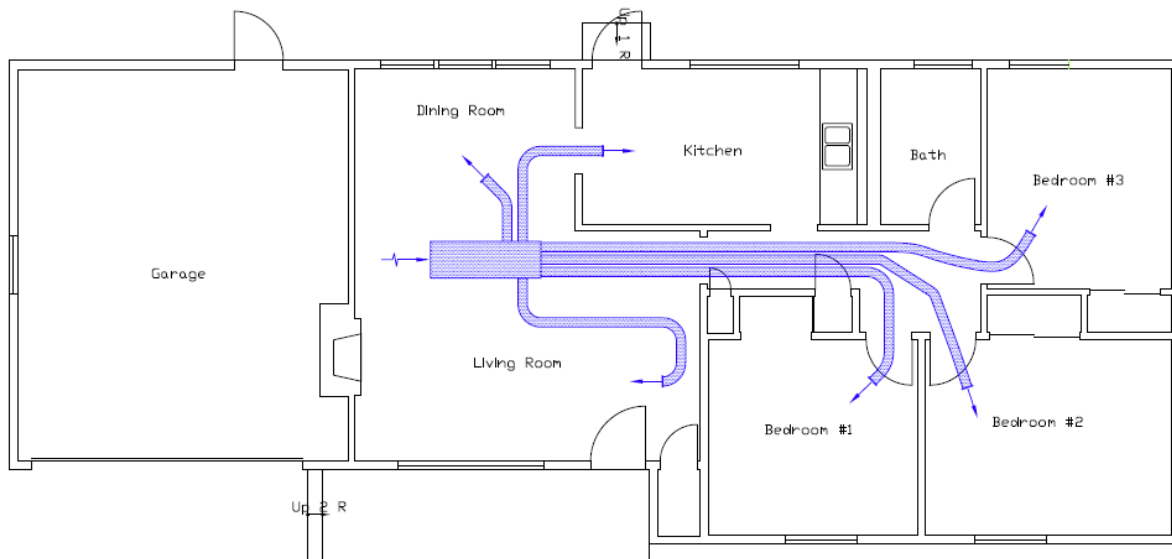


FIGURE 14. MAYFAIR FLOOR PLAN AND HVAC DISTRIBUTION SYSTEM LAYOUT

TEST PLAN

OPERATION SCHEDULE

COOLING MODE

The project applied a flip/flop experimental design at all three houses. The data acquisition system (DAS) control system alternated between the three heat pump systems at each house over an eight-day rotation as listed in Table 9. System changeover occurred at midnight. All systems were operated at a constant thermostat setpoint, with thermostat settings adjusted at the start of the monitoring period to produce average indoor temperatures as close as possible to 74°F. Refrigerant levels in the VCHP systems were adjusted during the summer, while refrigerant levels for the reference HP systems remained unchanged. The refrigerant adjustment schedule is shown in Table 10.

TABLE 9. SUMMER 2019 HVAC SYSTEM OPERATION DURING EIGHT-DAY ROTATIONS

DAYS	THERMOSTAT SETPOINT (°F)
1, 2	Reference HP at 100% Refrigerant
3, 4, 5	VCHP #1 at Varying Refrigerant Levels
6, 7, 8	VCHP #2 at Varying Refrigerant Levels

TABLE 10. VCHP REFRIGERANT LEVELS DURING THE SUMMER 2019 COOLING SEASON

SEASON	100% REFRIGERANT	80% REFRIGERANT	65% REFRIGERANT	50% REFRIGERANT
Summer Cooling 2019	June 9 – June 16			
				June 19 – July 10
	July 13 – July 18			
			July 21 – August 11	
		Aug 14 – Sept 4		
	Sept 7 – Sept 28			

HEATING MODE

The project applied a flip/flop experimental design at all three houses. The data acquisition system (DAS) control system alternated between the VCHP systems and electric resistance heaters at each house over an eight-day rotation as listed in Table 11. System changeover occurred at 7 AM in order to create a heating day that captures solar and thermal mass effects in the same 24 hour period as the heating loads resulting from those effects. All systems were operated at a constant thermostat setpoint, with thermostat settings adjusted to produce average indoor temperatures as close as possible to 68°F at the start of the monitoring period. Refrigerant levels in the VCHP systems were adjusted during the winter. The refrigerant adjustment schedule is shown in Table 12.

TABLE 11. WINTER 2019-20 HVAC SYSTEM OPERATION DURING EIGHT-DAY ROTATIONS

DAYS	THERMOSTAT SETPOINT (°F)
1, 2	Reference Electric Resistance Heat
3, 4, 5	VCHP #1 at Varying Refrigerant Levels
6, 7, 8	VCHP #2 at Varying Refrigerant Levels

TABLE 12. VCHP REFRIGERANT LEVELS DURING THE WINTER 2019-20 HEATING SEASON

SEASON	100% REFRIGERANT	80% REFRIGERANT	65% REFRIGERANT	50% REFRIGERANT
Winter Heating 2019-20	Nov 26 – Dec 9			
		Dec 12 – Jan 2		
				Jan 5 – Jan 26
	Jan 29 – Feb 11			
			Feb 14 – Mar 12	
	Mar 14 – Mar 31			

REFRIGERANT ADJUSTMENT PROCEDURE

EQUIPMENT AND SETUP

The electronic scale used for all measurements was a Yellow Jacket Refrigerant Recovery Scale Model #68862 with rated capacity of 220 LB, manufacturer stated accuracy of $\pm 0.05\%$ of reading, and a display resolution of one-hundredth of a pound (0.01 LB). The accuracy of the refrigerant scale was verified on each day that refrigerant adjustments were performed. The scale was placed on a flat surface, zeroed, and tested at 5, 10, 15, 20, 25, 30, and 35 lbs using a set of laboratory calibrated weights. In all cases, the scale reading was confirmed to be within 0.01 lb of the test weight.

A standard refrigerant hose with ball valve end was attached to a recovery bottle and the combination was weighed at the start and end of each adjustment.

A vacuum pump was installed in tandem to a refrigerant recovery machine with a system of isolation valves and hoses that enabled a deep (99.9%) vacuum to be established on all recovery components to ensure leak free connections prior to starting recovery.

A twin-cylinder recovery machine with manual controls was used to ensure a minimum volume of stored / unrecoverable refrigerant remained within the recovery unit. The manual control allows removal down to 99.5% vacuum (2500 Microns) instead of traditional 50% vacuum (15" Hg, 380,000 Microns) that automatic shutoff machines stop at.

ADJUSTMENT PROCEDURE

Refrigerant levels were defined as a percent of the manufacturer specified refrigerant amount. For the mini split VCHP systems at Grange and Mayfair, which were installed with the standard refrigerant line length, the manufacturer specified refrigerant amount equals the standard refrigerant weight indicated on the nameplate. For the multi split systems at Caleb, the manufacturer specified refrigerant amount equals the standard amount that the outdoor unit ships with, plus the manufacturer specified additional amount for the length of refrigerant lines installed to serve the multiple indoor units.

All systems were fully evacuated, and the manufacturer specified refrigerant amount was weighed in at the beginning of cooling season and again at the beginning of heating season. Additional checkpoints with full refrigerant evacuation were performed for all VCHP systems in mid July prior to the 65% refrigerant charge test, and for the Caleb VCHP systems in early January prior to the 80% test. The adjustments to other refrigerant levels were performed incrementally.

For refrigerant adjustments that involved removing partial system charge, the recovery bottle and connecting hose were weighed at the start and end of the process and the net change was recorded as the adjustment. Subsequently, the recovery machine was isolated and removed from the set-up and placed on the refrigerant scale along with any connecting hoses and any remaining gas inside. The trace refrigerant was released by opening a valve, and the weight of "trapped" charge was recorded as the net change in weight (pre and post charge release). Typical values ranged from zero to a high of 0.02 LB (9 grams) of trapped gas charge. The gross recovered charge plus the "trapped" charge equaled the net

recovered charge. The net recovered charge was divided by the heat pump system charge as determined from manufacturer labeled value plus connecting line-set adjustment to calculate the total percentage of system charge that was removed.

For adjustments that involved the addition of refrigerant, virgin R-410A was used and the addition was performed with the bottle in an inverted position to ensure appropriate refrigerant composition. A hose remained on the bottle and remained filled with refrigerant for the start and end weighing process such that the difference in weight equaled the net charge addition. The hose was connected at the unit service port using only a valve core removal tool such that only a trace amount of refrigerant gas could remain within the tool upon disconnection.

Whenever the adjustment plan called for removal of the entire refrigerant amount, the recovery bottle and contents were chilled to 40-45° F (120-130 PSI) during the process to improve recovery vacuum and ensure repeatability at different weather conditions.

OCCUPANCY SIMULATION

Internal heat gains due to occupants and appliances were simulated using electric heaters and a humidifier. The equipment was programmed to produce heat and moisture to match sensible and latent heat gain profiles used in Title 24 compliance software (CEC 2019). The sensible heat gain profiles are shown in Table 13 and the latent heat gain profiles are shown in Table 14. The gains were varied monthly per the multipliers in Table 15.

The electric heaters that simulate the sensible heat gain were turned on every 5 minutes for the amount of time necessary to provide the specified average heat rate for the hour. The humidifiers that simulate the latent heat gain were turned on every 15 minutes and operated for the amount of time necessary to provide the desired average latent heat rate for the hour. The humidifiers were operated only during the summer season for this study.



FIGURE 15. EQUIPMENT USED TO SIMULATE OCCUPANCY

TABLE 13. INTERNAL SENSIBLE HEAT GAIN PROFILES

Hour	CALEB (kWh [BTU])	GRANGE (kWh [BTU])	MAYFAIR (kWh [BTU])
1	0.473 [1613]	0.309 [1054]	0.332 [1134]
2	0.446 [1521]	0.295 [1005]	0.316 [1080]
3	0.426 [1453]	0.285 [971]	0.305 [1040]
4	0.432 [1473]	0.287 [979]	0.308 [1051]
5	0.428 [1461]	0.285 [971]	0.306 [1043]
6	0.571 [1949]	0.399 [1361]	0.424 [1447]
7	0.729 [2488]	0.518 [1768]	0.55 [1877]
8	0.649 [2215]	0.432 [1475]	0.465 [1587]
9	0.479 [1633]	0.297 [1014]	0.324 [1106]
10	0.38 [1298]	0.224 [764]	0.248 [845]
11	0.382 [1303]	0.226 [770]	0.248 [848]
12	0.376 [1283]	0.223 [762]	0.245 [836]
13	0.357 [1217]	0.213 [727]	0.233 [796]
14	0.364 [1243]	0.217 [741]	0.238 [813]
15	0.397 [1355]	0.243 [828]	0.265 [905]
16	0.454 [1550]	0.285 [974]	0.311 [1060]
17	0.571 [1949]	0.37 [1263]	0.4 [1364]
18	0.727 [2482]	0.475 [1622]	0.512 [1748]
19	0.93 [3173]	0.599 [2043]	0.649 [2215]
20	1.095 [3735]	0.704 [2402]	0.765 [2611]
21	1.095 [3738]	0.706 [2407]	0.766 [2614]
22	0.988 [3371]	0.632 [2155]	0.686 [2341]
23	0.769 [2625]	0.491 [1676]	0.533 [1820]
24	0.58 [1977]	0.364 [1243]	0.395 [1349]

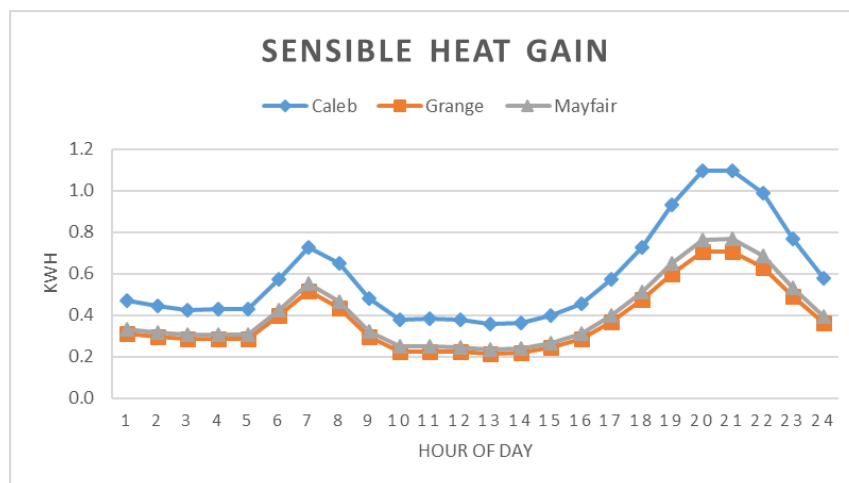


FIGURE 16. SENSIBLE HEAT GAIN PROFILE

TABLE 14. INTERNAL LATENT HEAT GAIN PROFILES

HOUR	CALEB		GRANGE		MAYFAIR	
	(kWh [BTU])	(LITERS)	(kWh [BTU])	(LITERS)	(kWh [BTU])	(LITERS)
1	0.149 [508]	0.218	0.124 [421]	0.181	0.125 [427]	0.184
2	0.145 [496]	0.213	0.121 [413]	0.178	0.123 [419]	0.18
3	0.145 [493]	0.212	0.12 [410]	0.176	0.122 [416]	0.179
4	0.145 [493]	0.212	0.12 [410]	0.176	0.122 [416]	0.179
5	0.141 [482]	0.207	0.118 [404]	0.174	0.12 [410]	0.176
6	0.208 [711]	0.306	0.183 [625]	0.269	0.186 [634]	0.273
7	0.277 [946]	0.407	0.248 [846]	0.364	0.25 [852]	0.366
8	0.211 [720]	0.309	0.181 [616]	0.265	0.183 [625]	0.269
9	0.129 [439]	0.189	0.103 [350]	0.15	0.104 [356]	0.153
10	0.087 [298]	0.128	0.065 [222]	0.095	0.067 [227]	0.098
11	0.089 [304]	0.131	0.066 [225]	0.097	0.067 [230]	0.099
12	0.089 [304]	0.131	0.066 [225]	0.097	0.067 [230]	0.099
13	0.087 [298]	0.128	0.065 [222]	0.095	0.067 [227]	0.098
14	0.089 [304]	0.131	0.066 [225]	0.097	0.067 [230]	0.099
15	0.105 [358]	0.154	0.08 [274]	0.118	0.082 [280]	0.121
16	0.129 [439]	0.189	0.103 [350]	0.15	0.104 [356]	0.153
17	0.176 [599]	0.258	0.145 [493]	0.212	0.147 [502]	0.216
18	0.226 [771]	0.332	0.189 [645]	0.277	0.192 [654]	0.281
19	0.267 [912]	0.392	0.227 [774]	0.333	0.229 [783]	0.337
20	0.306 [1044]	0.449	0.264 [900]	0.387	0.267 [912]	0.392
21	0.309 [1055]	0.454	0.266 [909]	0.391	0.269 [918]	0.395
22	0.276 [940]	0.404	0.234 [797]	0.343	0.236 [806]	0.346
23	0.219 [748]	0.322	0.183 [625]	0.269	0.186 [634]	0.273
24	0.162 [553]	0.238	0.13 [444]	0.191	0.133 [453]	0.195

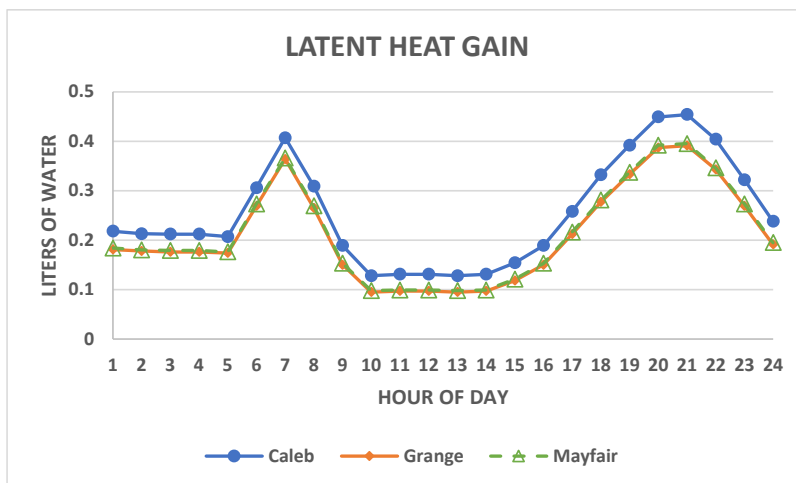


FIGURE 17. LATENT HEAT GAIN PROFILE

TABLE 15. INTERNAL HEAT GAIN MONTHLY MULTIPLIERS – USED FOR BOTH SENSIBLE AND LATENT HEAT GAINS

MONTH	MULTIPLIER
January	1.19
February	1.11
March	1.02
April	0.93
May	0.84
June	0.80
July	0.82
August	0.88
September	0.98
October	1.07
November	1.16
December	1.21

INSTRUMENTATION PLAN

The team installed monitoring and control systems in each home. These systems control the operation of the HVAC and internal gain systems and allow for switching between the HVAC systems. The team instrumented the research homes to provide hourly and minute-by-minute data. The monitoring equipment also controlled the humidifiers and heaters to simulate latent and sensible heat gain from occupants.

KEY MONITORED DATA POINTS

The following monitored data points were used in the analysis:

- Dry bulb air temperature in each conditioned room
- Indoor relative humidity
- Outdoor temperature
- Outdoor humidity
- Electrical energy of electric resistance heaters and other interior electrical loads applied as sensible gains
- Liters of water added through the humidifier as latent gains
- Pressure difference from the house to outside

Heat pump units

- Indoor unit power and energy
- Outdoor unit power and energy
- Supply air temperature
- Return air temperature
- Liters of condensate removal

SENSOR SPECIFICATIONS, LOCATIONS, AND CALIBRATION

The measurements made for this study are listed for each house in Table 16 through Table 18, along with sensor specifications and sensor locations. The rooms listed in these tables can be identified in the floorplans of Figure 18 through Figure 21.

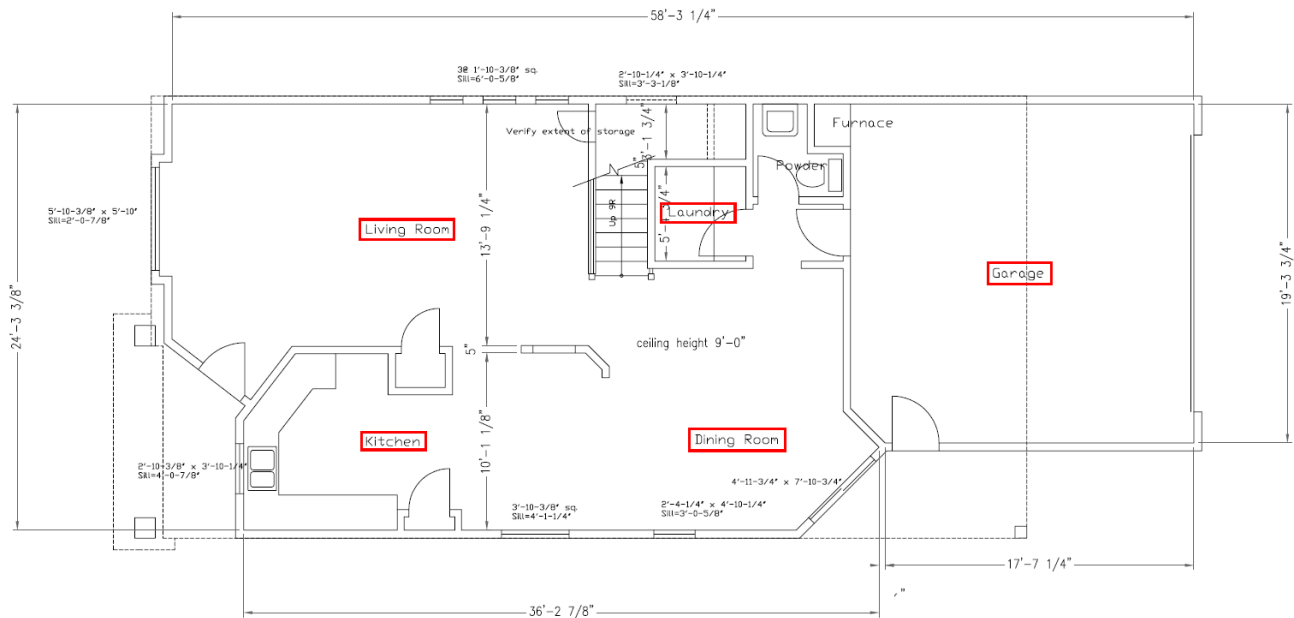


FIGURE 18. CALEB FLOOR PLAN – LOWER FLOOR

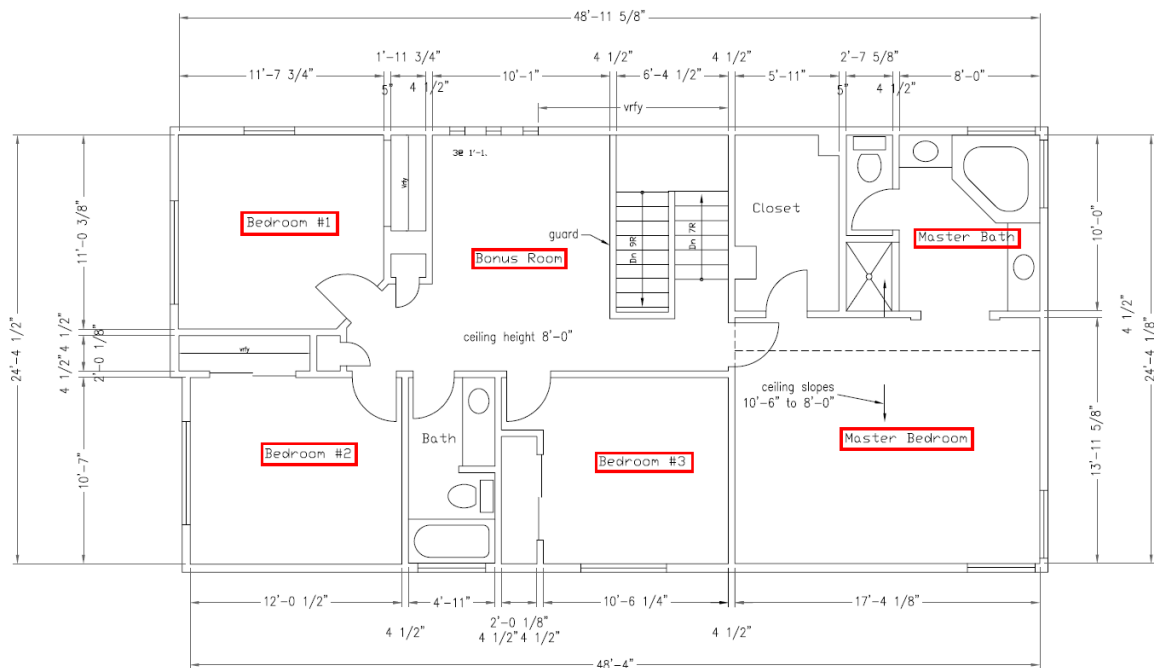


FIGURE 19. CALEB FLOOR PLAN – UPPER FLOOR

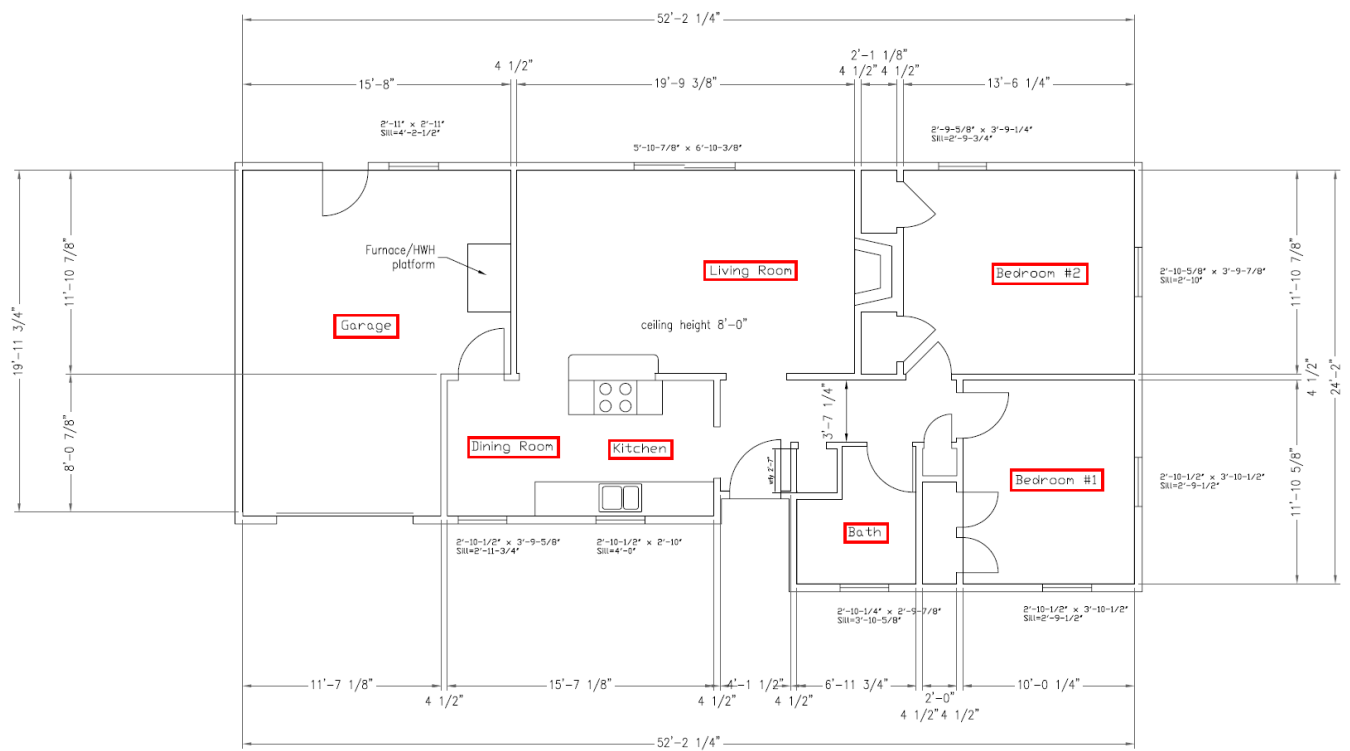


FIGURE 20. GRANGE FLOOR PLAN

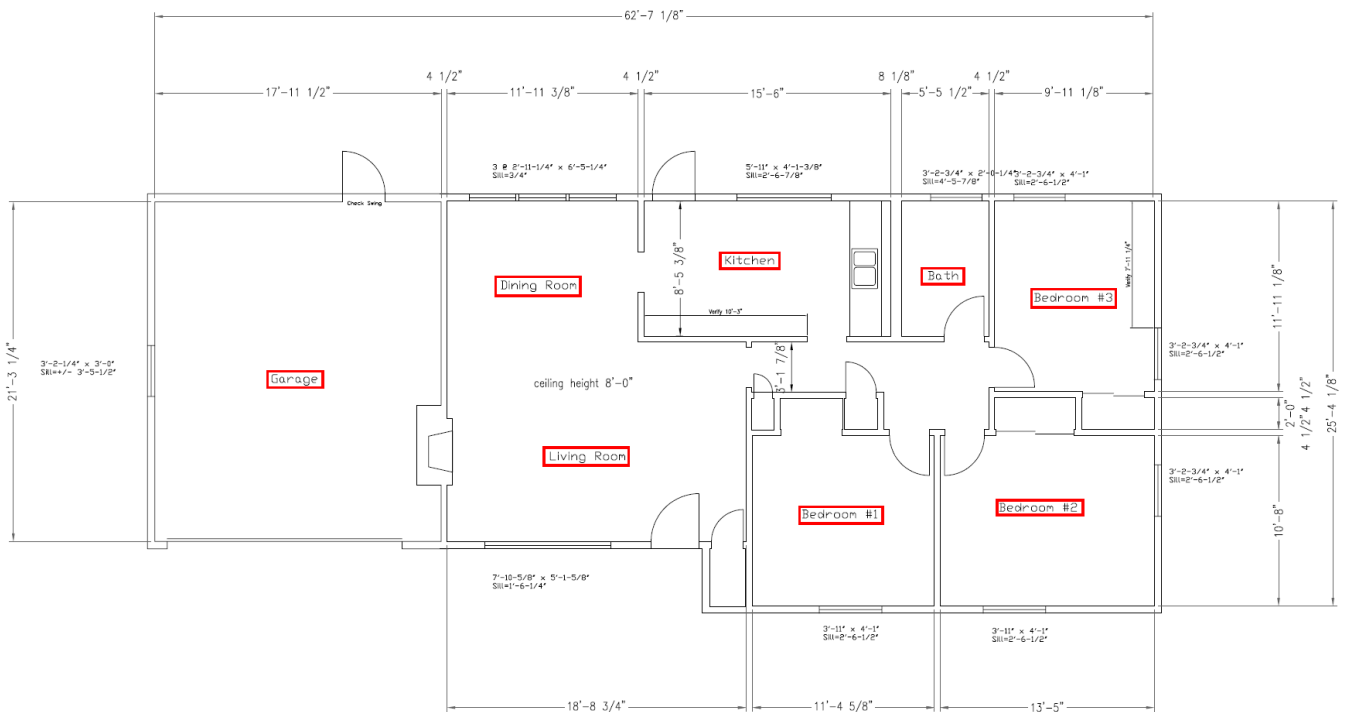


FIGURE 21. MAYFAIR FLOOR PLAN

TABLE 16. SENSOR SPECIFICATIONS AND LOCATIONS - CALEB

MEASUREMENT	SENSOR	LOCATION(S)
Air temperature	Shielded and aspirated thermocouple – Type T. Omega 24 ga TW SH STR	• Mounting height 48 in., center of room: Living room, Kitchen, Laundry, Bedroom 1, Bedroom 2, Bedroom 3, Master bedroom, Master bath, Landing, Garage • Attic, midpoint between ceiling and roof • Thermostat 1st floor & 2nd floor • Supply air, reference system (8) • Supply air, ducted 1st floor (3) • Supply air, ducted 2nd floor (3) • Supply air, ductless heads (7) • Return air, reference system • Return air, ducted 1st floor • Return air, ducted 2nd floor
Air temperature & relative humidity	Vaisala HMP60 Relative humidity • 0 to 40C; +/-3% RH (0-90% RH); +/-5% RH (90-100% RH) Temperature: 10-30C, +/- 0.5C	Mounting height 48 in. • Living room • Bonus room
Air temperature & relative humidity	Vaisala HMP110 Relative humidity • 0 to 40C; +/-1.5% RH (0-90% RH); +/-2.5% RH (90-100% RH) Temperature: 0-40C, +/-0.2C	Mounting height 48 in., center of room • Dining room • Laundry • Bedrooms 1, 2, 3, Master • Master bath • Outdoors
Differential air pressure	Setra 264 very low pressure differential transducer • 0-150F; +/- 1% full scale	• Indoor at floor level in Dining Room to outdoors • Attic to outdoors
Electric energy	Watt Node – WNB-3D-240-P • Accuracy: +/-0.5% (CT current 5% - 100% of rated current)	• 50A CT, 1 turn: house total excluding HVAC • 30A CT, 1 turn: ductless VCHP outdoor unit • 15A CT, 3 turns: ductless VCHP indoor total • 5A CT, 3 turns, ductless indoor heads (4) • 30A CT, 1 turn: Reference HP outdoor unit • 5A CT, 1 turn: Reference HP indoor unit • 30A CT, 1 turn: ducted VCHP outdoor unit • 15A CT, 3 turns: ducted VCHP indoor 1st flr • 15A CT, 3 turns: ducted VCHP indoor 2nd flr
Electric current	CR Magnetics CR4210 • 0.5% avg RMS AC amps • 0 to 60C	• 5A CT, 3 turns: ductless VCHP indoor (3)
Electric energy	Watt Node – WNB-3Y-208-P	• 30A CT, 1 turn: sensible gain heaters (2)
Water flow to humidifier	Omega FTB-4605 Water meter • +/- 2% accuracy	• Kitchen
Air conditioner condensate	Texas Electronics TR525-I Tipping bucket • +/- 1% accuracy	• Dining Room

TABLE 17. SENSOR SPECIFICATIONS AND LOCATIONS - GRANGE

MEASUREMENT	SENSOR	LOCATION(S)
Air temperature	Shielded and aspirated thermocouple – Type T. Omega 24 ga TW SH STR	Mounting height 48 in., center of room • Living room • Kitchen • Bedrooms 1,2 • Bath • Garage • Attic (midpoint between ceiling and roof) • Thermostat • Supply air (8) • Return air
Air Temperature & relative humidity	Vaisala HMP60 Relative humidity • 0 to 40C; +/-3% RH (0 to 90% RH); +/-5% RH (90 to 100% RH) Temperature • 10-30C, +/-0.5C	• Mounting height 48 in. • Living room • Return air
Differential air pressure	Setra 264 very low pressure differential transducer • 0-150F; +/- 1% full scale	• Indoor to outdoor at floor level in Living Room • VCHP air filter
Electric energy	Watt Node – WNB-3D-240-P Accuracy: +/-0.5% (CT current 5% - 100% of rated current)	• 100A CT, 1 turn: house total excluding HVAC • 15A CT, 1 turn: VCHP systems 0.75 ton VCHP outdoor & indoor units & 1 ton VCHP outdoor & indoor units • 5A CT, 3 turns: VCHP indoor units 0.75 ton VCHP indoor unit & 1 ton VCHP indoor unit • 15A CT, 1 turn: Reference outdoor unit 2 ton HP outdoor unit • 5A CT, 1 turn: Reference indoor unit 2 ton HP indoor unit
Electric energy	Watt Node – WNB-3Y-208-P	• 30A CT, 1 turn: sensible gain heaters
Water flow to humidifier	Omega FTB-4605 Water meter +/- 2% accuracy	• Kitchen
Air conditioner condensate	Texas Electronics TR525-I Tipping bucket +/- 1% accuracy	• Dining Room

TABLE 18. SENSOR SPECIFICATIONS AND LOCATIONS - MAYFAIR

MEASUREMENT	SENSOR	LOCATION(S)
Air temperature	Shielded and aspirated thermocouple – Type T. Omega 24 ga TW SH STR	Mounting height 48 in., center of room • Dining room • Living room • Kitchen • Bedrooms 1, 2, 3 • Bath • Garage • Attic (midpoint between ceiling and roof) • Thermostat • Supply air, ducted systems (8) • Return air
Air Temperature & relative humidity	Vaisala HMP60 Relative humidity • 0 to 40C; +/-3% RH (0 to 90% RH); +/-5% RH (90 to 100% RH) Temperature • 10-30C; +/-0.5C	Mounting height 48 in. • Living room • Crawlspace (3)
Differential air pressure	Setra 264 very low pressure differential transducer • 0-150F; +/- 1% full scale	• Indoor to outdoor at floor level in Dining Room • Indoor to crawlspace at floor level in Dining Room
Electric energy	Watt Node – WNB-3D-240-P Accuracy: +/-0.5% (CT current 5% - 100% of rated current)	• 100A CT, 1 turn: house total excluding HVAC • 30A CT, 2 turns: VCHP systems 1.5 ton VCHP outdoor & indoor units & 2 ton VCHP outdoor & indoor units • 5A CT, 3 turns: VCHP indoor units 1.5 ton VCHP indoor unit & 2 ton VCHP indoor unit • 20A CT, 1 turn: Reference System 2 ton HP outdoor & indoor units • 5A CT, 2 turns: Reference indoor unit 2 ton HP indoor unit
Electric energy	Watt Node – WNB-3Y-208-P	• 30A CT, 1 turn: sensible gain heaters
Water flow to humidifier	Omega FTB-4605 Water meter +/- 2% accuracy	• Kitchen
Air conditioner condensate	Texas Electronics TR525-I Tipping bucket +/- 1% accuracy	• Dining Room

DATA LOGGER SPECIFICATIONS AND PROGRAMMING

Data was collected using the following set of Campbell Scientific equipment at each site.

- (1) CR1000 Measurement and Control System
- (2 or 3) AM16/32 multiplexer
- (2) SDM-SW8A 8-Channel Switch Closure Input Module
- (1) SDM-CD16AC 16-Channel AC/DC Relay Controller

The monitored data points were read every 20 seconds and the average (or sum as appropriate) was recorded every minute. Data was automatically downloaded by a remote server every 20 minutes.

The role of the system included equipment control as well as data collection. Outputs from the DAS controlled all equipment used to provide internal gains, enabled or disabled all heat pump systems, and controlled the electric resistance heaters.

MONITORING EQUIPMENT INSTALLATION AND CALIBRATION

The monitoring and control equipment was installed and commissioned in a previous phase of the CVRH project (Wilcox, 2016). Reconfiguration and commissioning to support the 2019-20 research plan was performed in the spring of 2019.

ELECTRIC ENERGY

New revenue-grade electrical energy meters were installed prior to the 2015 cooling season. The accuracy was verified by comparing 1-week totals to the utility electricity meter and were found to be within 1%.

AIR TEMPERATURE

Room air temperature thermocouples were verified using an ice bath to be accurate within 0.05°F.

RELATIVE HUMIDITY

Relative humidity sensors were checked by co-locating sensors for several hours and verifying that the sensors provided the same reading within 3%.

WATER FLOW TO HUMIDIFIER, AND WATER FLOW FROM CONDENSATE DRAIN

The water flow volume monitoring equipment was verified to be accurate within 1% using a graduated cylinder.

ANALYSIS METHODOLOGY

VCHP energy use relative to the reference heating and cooling system was analyzed to produce a seasonally normalized representation of VCHP energy performance at each refrigerant level. VCHP performance at each refrigerant undercharge condition was then compared to performance with correct refrigerant charge to determine the efficiency impact of low refrigerant levels.

The analysis approach differs from that of prior CVRH studies in the application of seasonal factors. It was necessary to apply different analysis methods because the fundamental experimental design was different. The prior CVRH studies continuously alternated between the scenarios being tested throughout the year, so each scenario was subjected to a similar range of seasonal conditions. It was not possible to continuously alternate between different refrigerant levels throughout the year. Each refrigerant level was tested at a different time of year with different seasonal influences on the heating and cooling loads. The analysis was designed to account for these differences.

VCHP energy performance relative to the reference heating and cooling system was modeled in two steps:

1. Monitored reference system daily energy use was modeled at each house as a function of daily average, daily maximum and daily minimum outdoor temperatures, and a seasonal factor representing length of daylight. The resulting regression models were used to estimate reference system energy use on days the VCHP systems were operating.
2. VCHP system daily energy use was modeled through regression against the model predicted daily reference system energy use. Each refrigerant level was represented as a variable in the regression, producing a model representing all four refrigerant levels relative to each other.

The resulting models were applied to the Title 24 (2019) weather file for Stockton, CA to estimate annual energy and efficiency impacts of low refrigerant levels during a typical year.

The regressions were performed using only the temperature dependent cooling or heating component of the HVAC system energy use. The following sources of energy use were subtracted from the HVAC daily energy use prior to performing the regressions, and were added to the regression predicted cooling and heating energy use when total seasonal HVAC energy use was calculated:

- Constant power draws from HVAC system electrical components: This was calculated as the average monitored energy use during times when the compressor was off and the indoor fan was off. These power draws were assumed to be constant 24 hours per day, including when the HVAC system is idle and when it is operating.
- Temperature dependent standby energy use, including crankcase heat and other controls that produce different standby power levels at different outdoor temperatures: This is treated separately from the temperature dependent cooling and heating energy use because the slope relative to outdoor temperature may be opposite of the slope of cooling and heating energy due to less frequent compressor operation resulting in increased crankcase heat operation at low load conditions. These power draws are assumed to only occur when the compressor is not running. Temperature dependent standby energy use was observed only in the Mayfair VCHP units and was estimated for that site through a separate regression of associated daily energy use against daily outdoor temperature as detailed in Appendix B.

REFERENCE SYSTEM DAILY ENERGY USE

Reference system daily energy use was modeled through regression against four variables:

- T_{Avg} = Daily average outdoor temperature
- T_{High} = Daily high outdoor temperature
- T_{Low} = Daily low outdoor temperature
- t_{Day} = Relative length of daylight, defined as the time between sunrise and sunset for each day divided by the time between sunrise and sunset on December 21st. This variable accounts for seasonal effects.

For heating season, the model represents the daily heating load of the house since the reference system is electric resistance heat with a heating efficiency, or COP of 1. For cooling season, it represents the cooling load of the house interacted with the cooling efficiency of the reference heat pump system.

The reference system model was applied to the days the VCHP systems were operating to produce a representation of daily heating and cooling loads to evaluate VCHP performance at each refrigerant level against.

VCHP DAILY ENERGY USE

VCHP daily energy use was modeled through regression against four variables:

- E_{Ref} = Modeled reference system daily energy use
- $E_{Ref_R50} = E_{Ref} \times R50$, where:
 $R50 = 1$ on days the VCHP operated at 50% refrigerant charge
 $R50 = 0$ on all other days
- $E_{Ref_R65} = E_{Ref} \times R65$, where:
 $R65 = 1$ on days the VCHP operated at 65% refrigerant charge
 $R65 = 0$ on all other days
- $E_{Ref_R80} = E_{Ref} \times R80$, where:
 $R80 = 1$ on days the VCHP operated at 80% refrigerant charge
 $R80 = 0$ on all other days

This produces a model of VCHP energy use at all four refrigerant levels with the following characteristics:

- There is a single Y axis intercept regardless of refrigerant level. This means that the VCHP system is assumed to operate identically regardless of refrigerant level on a day with zero heating or cooling load as predicted by zero energy use by the reference system.
- The coefficient for E_{Ref} represents the slope of VCHP daily energy use against reference system daily energy use when the VCHP system is operating with correct refrigerant charge.

- The coefficients for $E_{Ref_R50} - E_{Ref_R80}$ represent the change in slope of VCHP daily energy use against the reference system daily energy use at each VCHP refrigerant undercharge level.

VCHP SEASONAL ENERGY USE

Typical seasonal VCHP energy use at each refrigerant level was evaluated by applying the reference system and VCHP daily energy use models to the Title 24 (2019) weather file for Stockton, CA. VCHP energy use at each refrigerant level was predicted by setting the R50-R80 variables to 1 or 0. Daily energy use associated with standby power and crankcase heat was added to the regression model predicted daily energy use. Total daily energy use was summed for all days in the year predicted by the reference system model to have heating or cooling loads greater than zero.

VCHP seasonal energy use is calculated as:

$$E_{VCHP_Seasonal_X} = \sum_1^n (E_{Ref_n} \times (F_{E_{Ref}} + F_{E_{Ref_RX}}) + C + E_{Standby}) + E_{CCH}$$

Where:

- X is the refrigerant level.
- n is the number of days in the year where the reference system regression model predicts there will be cooling energy use (for the cooling season annual energy use calculation) or heating energy use (for the heating season annual energy use calculation).
- $F_{E_{Ref}}$ is the regression coefficient for the E_{Ref} term in the VCHP vs. reference system daily energy use regression.
- $F_{E_{Ref_RX}}$ is the regression coefficient for the E_{Ref_RX} term in the VCHP vs. reference system daily energy use regression, for refrigerant level X.
- C is the constant from the VCHP vs. reference system daily energy use regression.
- $E_{Standby}$ is the VCHP daily standby energy use in kWh.
- E_{CCH} is the seasonal crankcase heat energy use in kWh. This is only used for the Mayfair VCHP systems. The calculation is detailed in Appendix B.
- E_{Ref_n} is the modeled reference system daily energy use in kWh for day n, calculated as:

$$E_{Ref_n} = T_{Avg} \times F_{T_{Avg}} + T_{High} \times F_{T_{High}} + T_{Low} \times F_{T_{Low}} + t_{Day} \times F_{t_{Day}} + C$$

Where:

- T_{Avg} is the daily average outdoor temperature for day n in °F, and $F_{T_{Avg}}$ is the corresponding regression coefficient.
- T_{High} is the daily high outdoor temperature for day n in °F, and $F_{T_{High}}$ is the corresponding regression coefficient.
- T_{Low} is the daily low outdoor temperature for day n in °F, and $F_{T_{Low}}$ is the corresponding regression coefficient.

- t_{Day} is the time between sunrise and sunset for day n divided by the time between sunrise and sunset on December 21st, and $F_{t_{Day}}$ is the corresponding regression coefficient.
- C is the regression constant.

RELATIVE VCHP PERFORMANCE AT EACH REFRIGERANT CHARGE LEVEL

Refrigerant undercharge impacts were evaluated by comparing modeled VCHP annual energy performance at each refrigerant undercharge level to performance with correct refrigerant charge.

VCHP energy use relative to energy use at correct refrigerant charge was calculated as:

$$VCHP \text{ Normalized Energy Use}_x = \frac{E_{VCHP_Seasonal_x}}{E_{VCHP_Seasonal_{100}}}$$

Where: $E_{VCHP_Seasonal}$ is the seasonal energy use predicted by the regression analysis for the VCHP at $X\%$ refrigerant charge and 100% refrigerant charge

The relative efficiency implied by the normalized energy use, if delivered capacity is assumed to be identical at the correctly charged and undercharged conditions is:

$$VCHP \text{ Normalized Efficiency}_x = \frac{1}{VCHP \text{ Normalized Energy Use}_x}$$

The assumption that the same capacity was delivered is not necessarily true in all cases. In some cases, most notably the Mayfair 1.5 ton VCHP in cooling season, the monitored indoor temperatures show that the same capacity was not being delivered at different refrigerant levels, with less capacity delivered with low refrigerant charge. For these cases, the efficiency calculated based on relative daily energy use underestimates efficiency losses at reduced refrigerant charge.

CORRECTION FOR INDOOR TEMPERATURE DIFFERENCES AT SYSTEM CHANGEOVER

This study applied a flip/flop experimental design, meaning that the DAS control system continually rotated between HVAC systems throughout the course of the study. This approach has the advantage of minimizing weather or seasonal effects since each system is operated throughout the study period and experiences similar weather and seasonal conditions. A challenge in the flip/flop design is that if indoor temperatures are not perfectly matched at the changeover from one system to the next, cooling or heating energy use may be affected during the first few hours that each system operates.

In some cases, indoor temperature differences at system changeover were larger in the 2019 study than in prior studies. This was caused in some cases by capacity and operational effects of low refrigerant charge, and in some cases by imperfectly matched thermostat settings between systems. Indoor temperature matching

between HVAC systems is challenging because thermostat to thermostat differences exist, and because many VCHP systems do not control indoor temperature exactly to setpoint at all times. In most cases indoor temperatures were closely matched, but in some cases temperature differences existed and affected energy use at system changeover.

For example, Figure 22 plots hourly average temperatures and hourly HVAC system energy use for the 12 hours prior to and 2 days after a transition from the ductless VCHP to the reference HP at the Caleb house during cooling season. The reference HP pulled the house temperature down by about 2 °F following system changeover on 9/13. Outdoor temperatures were similar on 9/13 and 9/14, but morning energy use was much higher on 9/13.

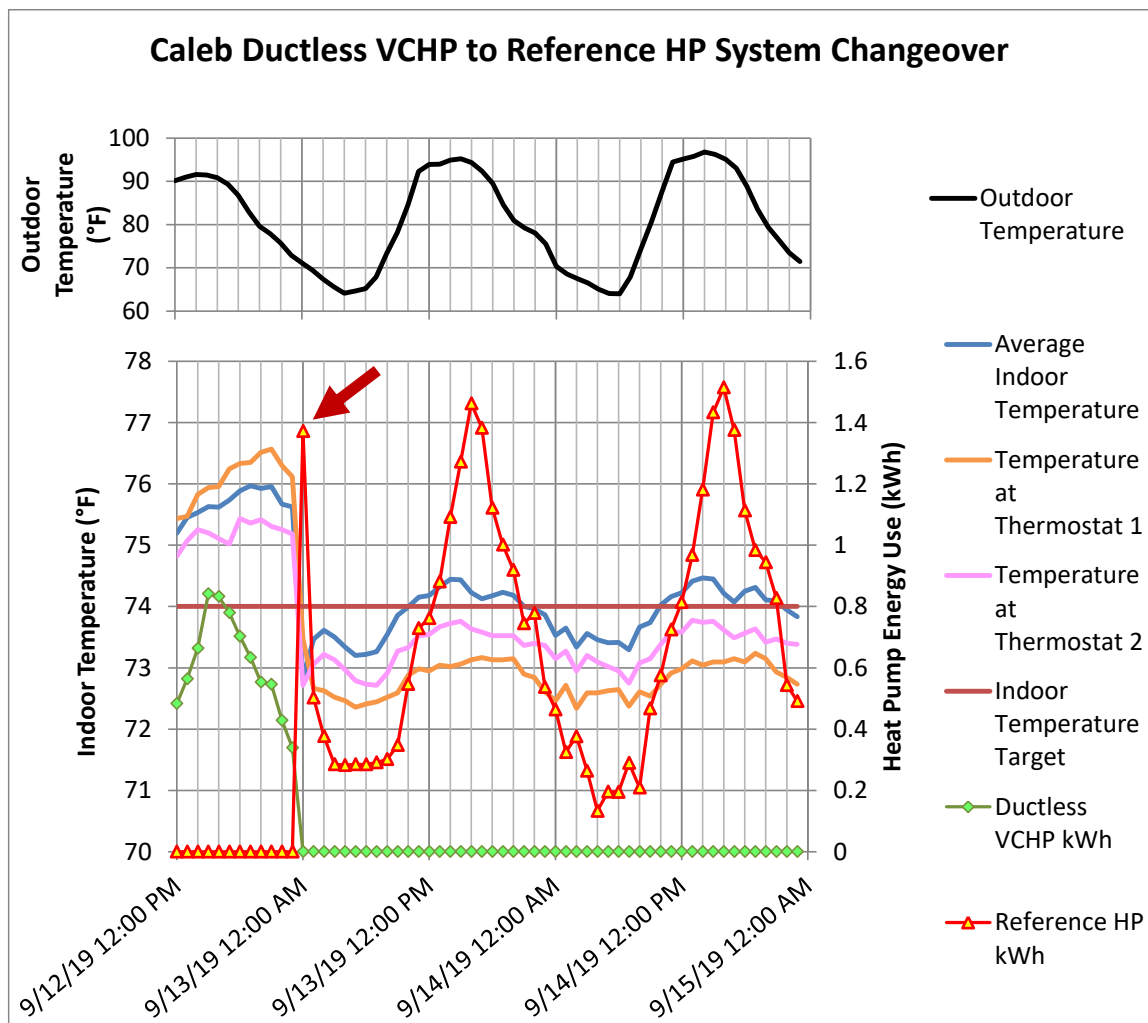


FIGURE 22. CALEB INDOOR TEMPERATURE DIFFERENCE AND INCREASED ENERGY USE AT SYSTEM CHANGEOVER

To correct for energy impacts of indoor temperature differences at system changeover during cooling season, energy use between midnight and 6AM was modeled for the 2nd and 3rd days each system operated. The modeled early morning

energy use was then applied to the 1st day the system operated following system changeover. This process was performed separately for each refrigerant level test period for each HVAC system.

This approach is based on the assumption that morning energy use on days 2 and 3 of the cycle is representative of what would be expected if the system was operating continuously every day. Therefore, replacing the day 1 midnight to 6AM energy use with the modeled amount produces a day 1 consistent with days 2 and 3, and representative of typical operation for the test scenario. For consistency, the correction was applied to all HVAC systems and all refrigerant charge scenarios even if there was no obvious difference in indoor temperature at system changeover.

The model was developed by regression of energy use against three factors related to cooling loads between midnight and 6AM:

- Average outdoor temperature from midnight to 6AM (the six hours following system change over) – this factor represents current conditions during the period being modeled.
- Average outdoor temperature from 6PM to midnight the preceding day (the six hours prior to system changeover) – this factor represents load effects from the immediately preceding time period.
- Daily high temperature of the preceding day – this factor represents load effects from the preceding afternoon, some of which may carry over into the current day if the HVAC system failed to meet loads during the preceding afternoon.

A similar approach was applied during heating season, with energy use during the 6 hours following system changeover at 7 AM modeled as a function of:

- Average outdoor temperature during the 6 hours prior to system changeover
- Average outdoor temperature during the 6 hours following system changeover

The regression results for system changeover energy use adjustments are provided in Appendix A.

These corrections were applied to the monitored energy use prior to performing the daily energy analysis.

RESULTS

Results are presented by house and heat pump system.

CALEB HOUSE, REFERENCE SYSTEM

Average temperatures of each room relative to the target temperature are shown in Figure 23 for times when the reference HP system was operating during cooling season, and for times when the electric resistance heaters were operating during heating season. The plotted values represent the average temperatures during hours with compressor operation during the hour, indicating that the system was providing

cooling to the house during the hour. Hours with no heat pump operation because there was no cooling load were excluded from the averages. The reference heat pump system has two zones of control, with the first floor zone (kitchen and living room) thermostat located in the living room and the second floor zone (landing and bedrooms) thermostat located in the landing. The electric resistance heaters in each room are individually controlled by the DAS system based on the monitored temperature in the room. The reference systems maintained average temperatures within 2 °F of target. Bedroom temperatures increased at warmer outdoor conditions due to solar gains in the afternoon.

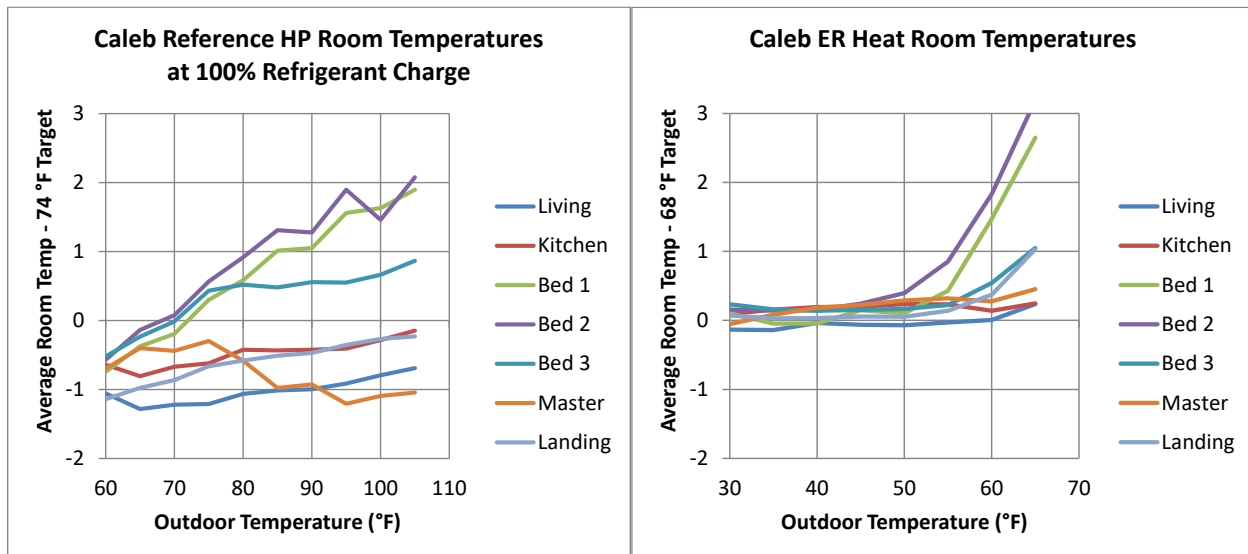


FIGURE 23. CALEB REFERENCE SYSTEM INDOOR TEMPERATURE DELTA TO TARGET

DAILY ENERGY USE

The daily energy use regression results for the reference HP and electric resistance heat are shown in Table 19. Figure 24 displays monitored daily energy use and the regression model for cooling season, and Figure 25 displays the monitored data and the regression model for heating season.

TABLE 19. CALEB REFERENCE SYSTEM DAILY ENERGY USE REGRESSIONS

SEASON	T _{AVG}	T _{HIGH}	T _{LOW}	t _{DAY}	CONST	R ²	DAILY STANDBY KWH
Cooling	0.0579	0.4628	0.4546	-4.6313	-56.5211	0.98	0.55
Heating	-0.8226	-1.2469	-0.6259	-7.2503	173.22	0.94	0

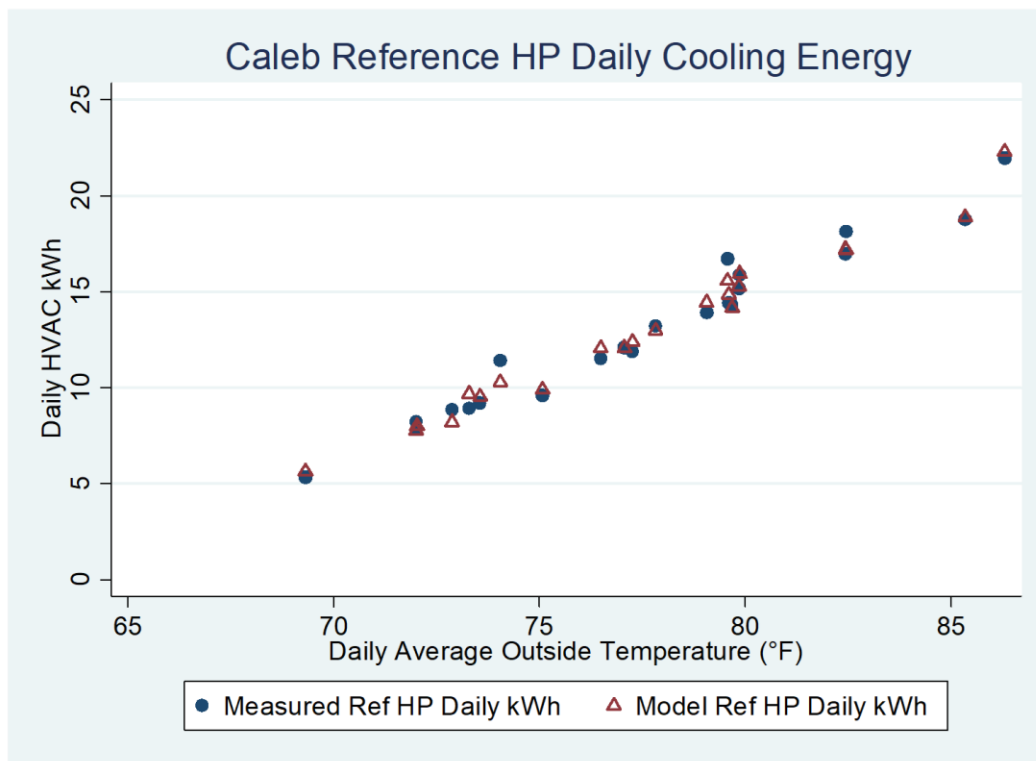


FIGURE 24. CALEB REFERENCE HP DAILY COOLING ENERGY REGRESSION MODEL

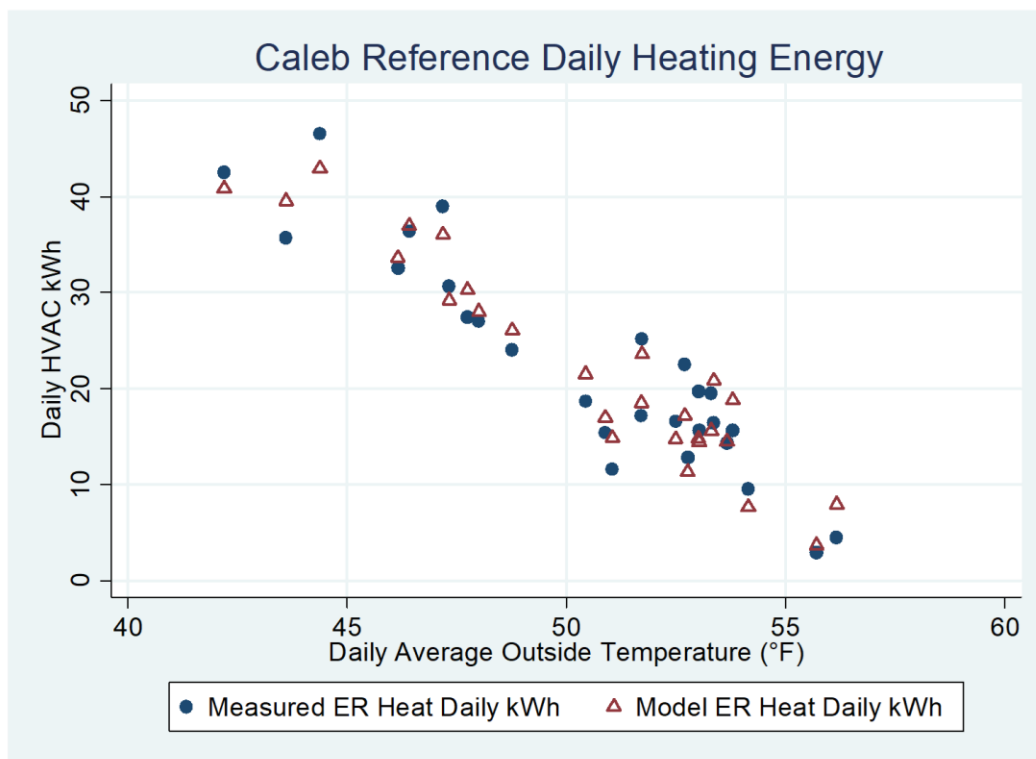


FIGURE 25. CALEB ELECTRIC RESISTANCE HEAT DAILY ENERGY REGRESSION MODEL

CALEB HOUSE, DUCTED VCHP

COOLING SEASON

The Ducted VCHP system maintained similar indoor temperatures at most refrigerant levels and outdoor temperatures. Average indoor temperature did increase by about 1.2 °F on hot afternoons at 50% undercharge relative to the 100% charge case.

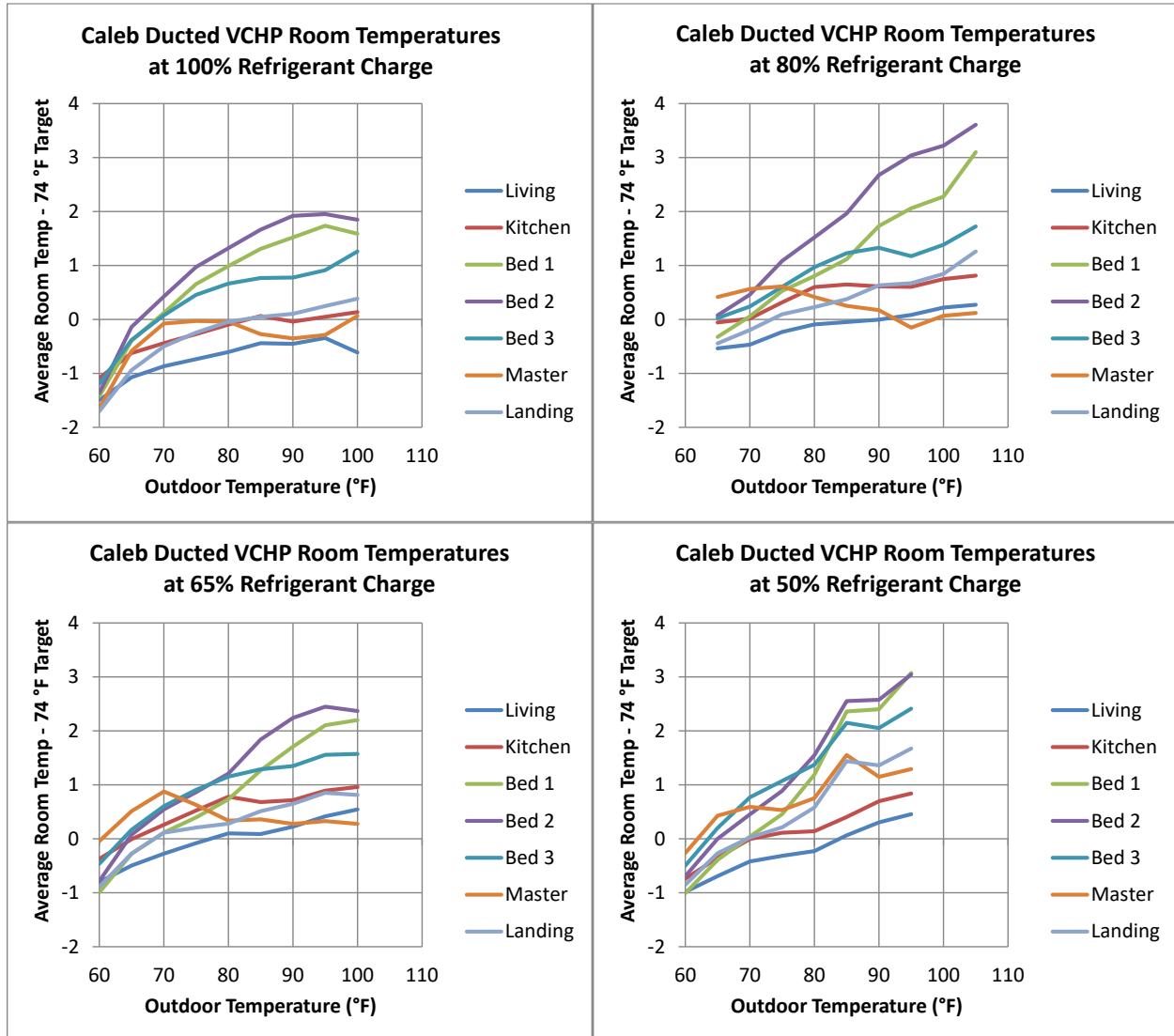


FIGURE 26. CALEB DUCTED VCHP COOLING SEASON INDOOR TEMPERATURE DELTA TO TARGET

Average temperatures of each room relative to the target temperature are shown in Figure 26. Average indoor temperatures relative to the temperatures at correct refrigerant charge are shown in Figure 27. The plotted values represent the average temperatures during hours with compressor operation during the hour, indicating

that the system was providing cooling to the house during the hour. Hours with no heat pump operation because there was no cooling load were excluded from the averages. The first floor of this house (living room and kitchen) is controlled by a thermostat located in the living room, and the second floor (landing and bedrooms) is controlled by a thermostat located in the landing.

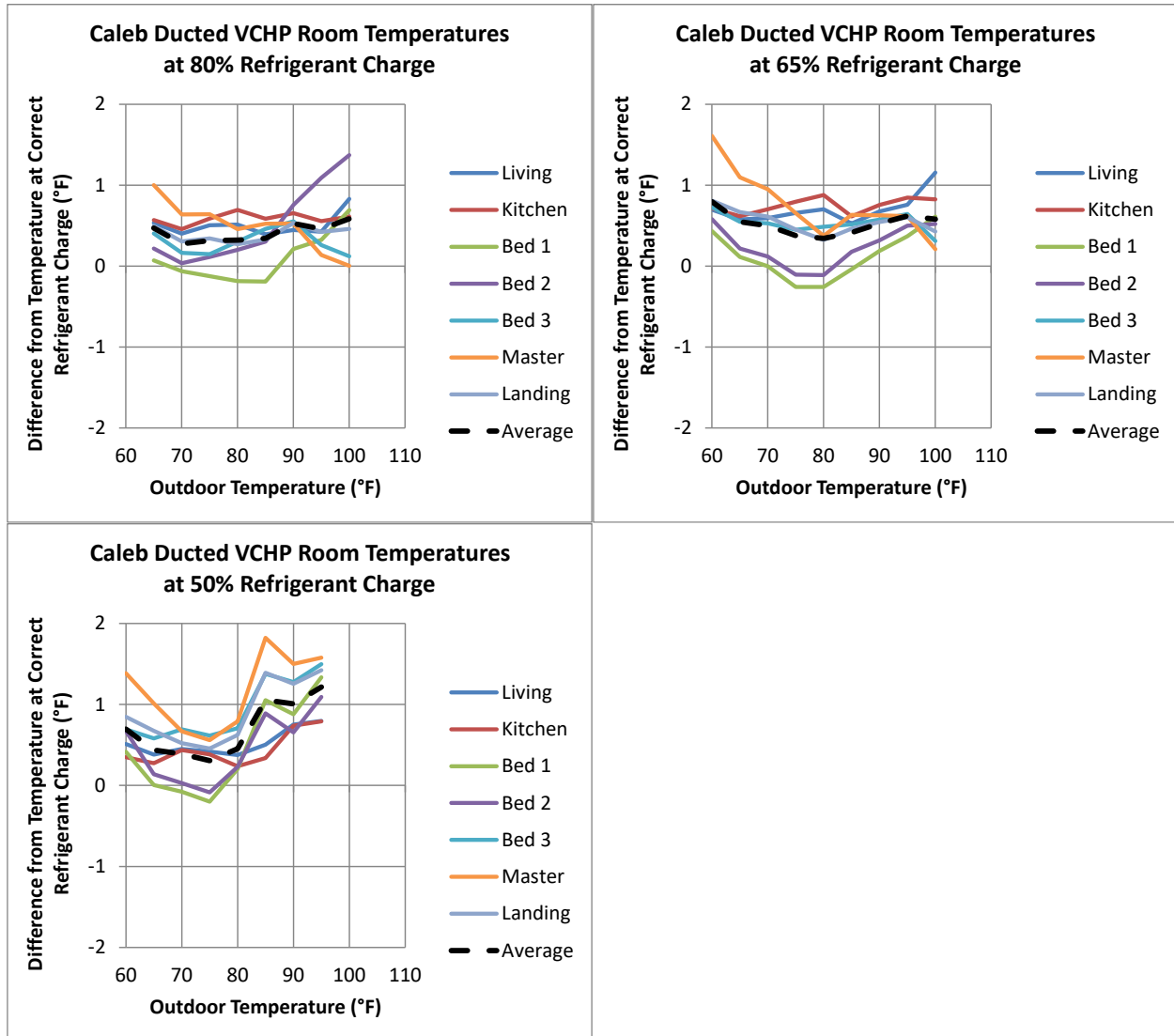


FIGURE 27. CALEB DUCTED VCHP COOLING SEASON INDOOR TEMPERATURES AT REFRIGERANT UNDERCHARGE CONDITIONS RELATIVE TO TEMPERATURES AT CORRECT REFRIGERANT CHARGE

Figure 28 and Figure 29 show examples of how this system operated on days with similar outdoor temperature at correct refrigerant charge and at 50% refrigerant charge. Each plotted point represents one minute. Apparent scatter in the outdoor unit power reflects cycling. This system tended to run frequent short cycles at lower load conditions.

In the morning of both days, when outdoor temperatures were mild and cooling loads were low, the system cycled and maintained indoor temperatures near target. As outdoor temperature warmed and cooling loads increased, the system settled into constant low speed operation. At correct refrigerant charge, the system continued operating at low speed through the afternoon and indoor temperatures remained near target. At 50% refrigerant charge, indoor temperatures climbed to 2 °F above target at 4PM, at which point the system began operating at a higher speed. In the late evening of both days, the system returned to cycling.

Figure 28 and Figure 29 show that indoor temperatures were not as well controlled with low refrigerant charge, and the system operated at higher speed and input power through the afternoon and into the evening.

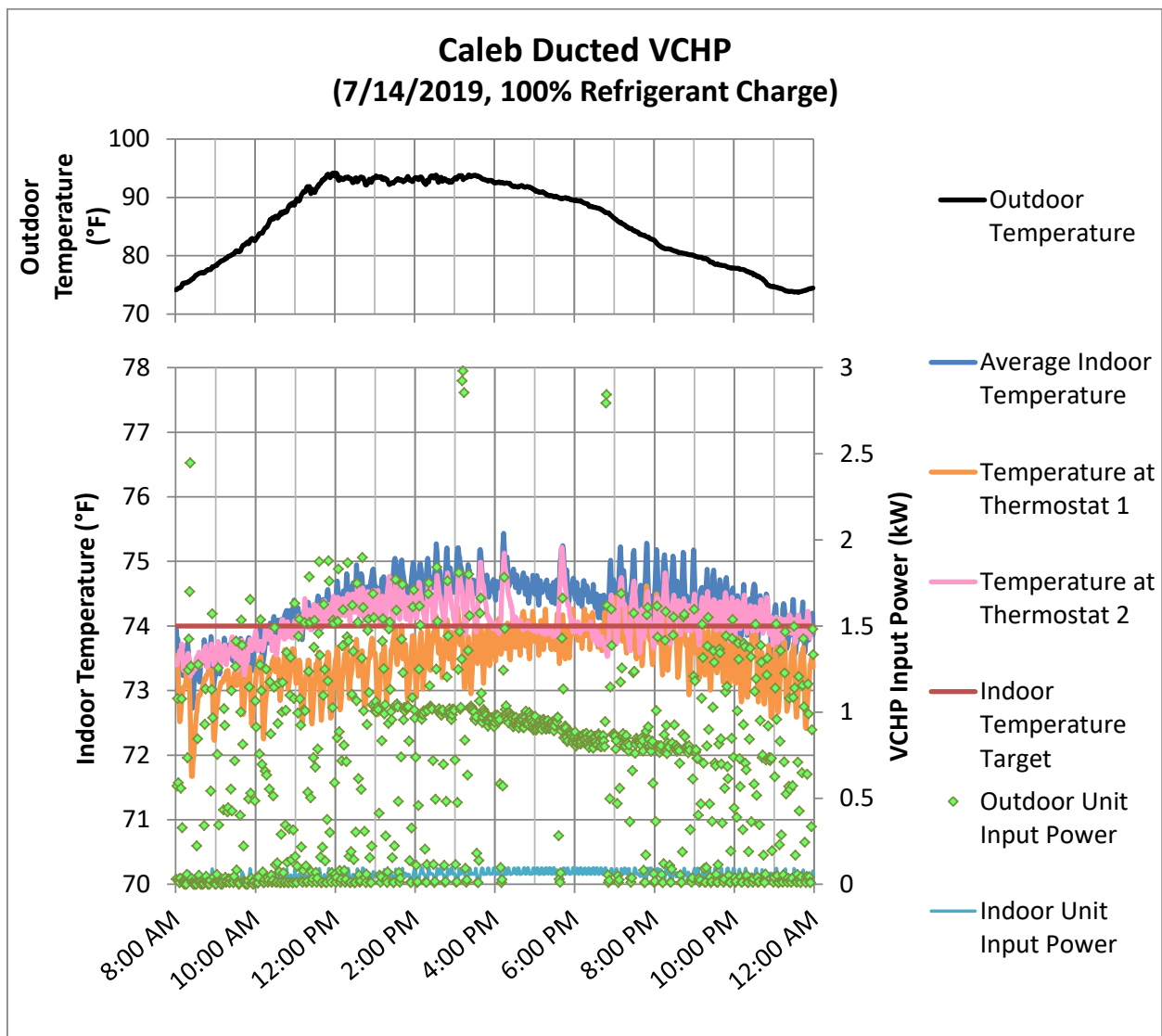


FIGURE 28. CALEB DUCTED VCHP COOLING EXAMPLE, CORRECT REFRIGERANT CHARGE

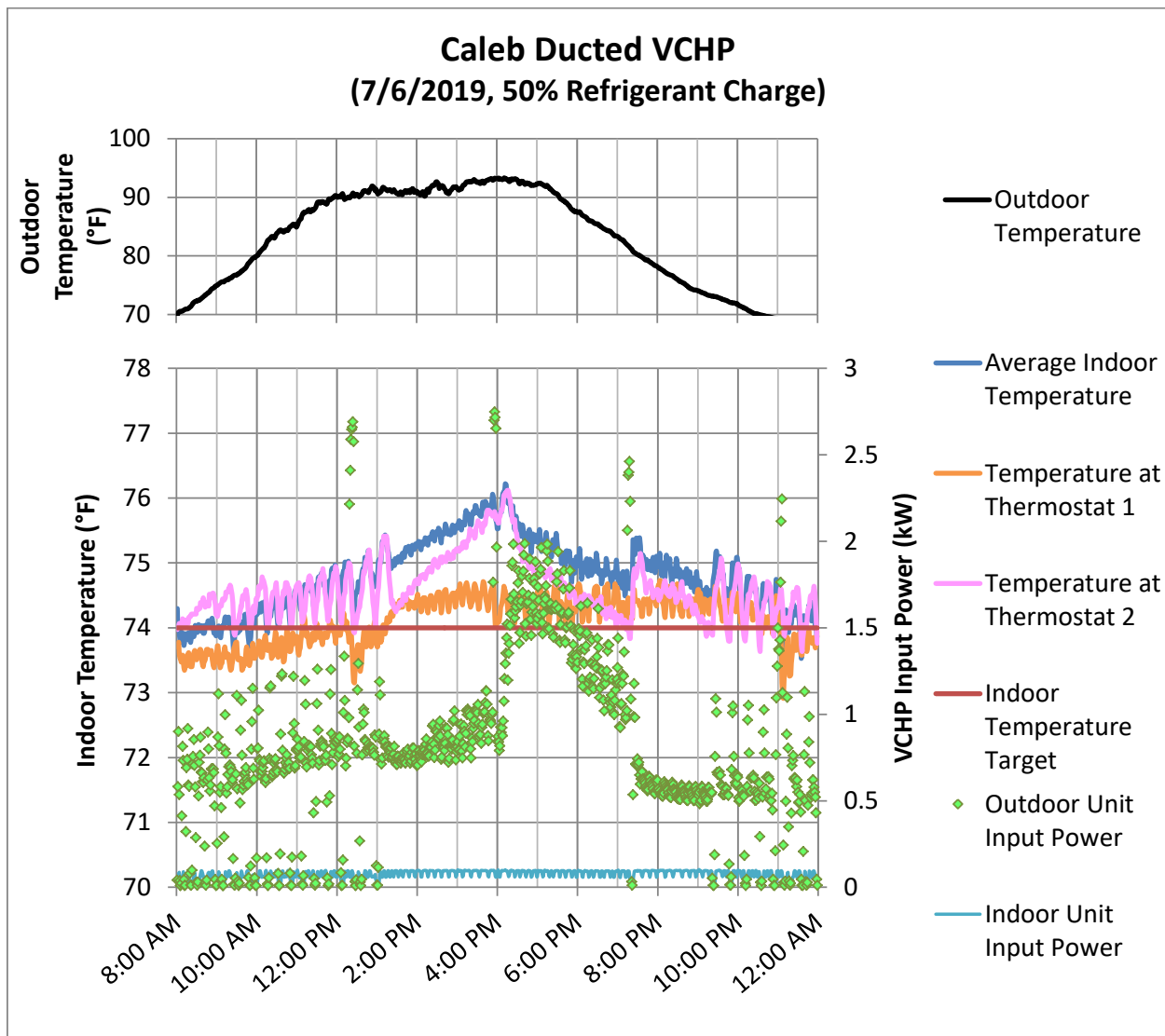


FIGURE 29. CALEB DUCTED VCHP COOLING EXAMPLE, 50% REFRIGERANT CHARGE

Figure 30 and Figure 31 show similar days at 65% and 80% refrigerant charge.

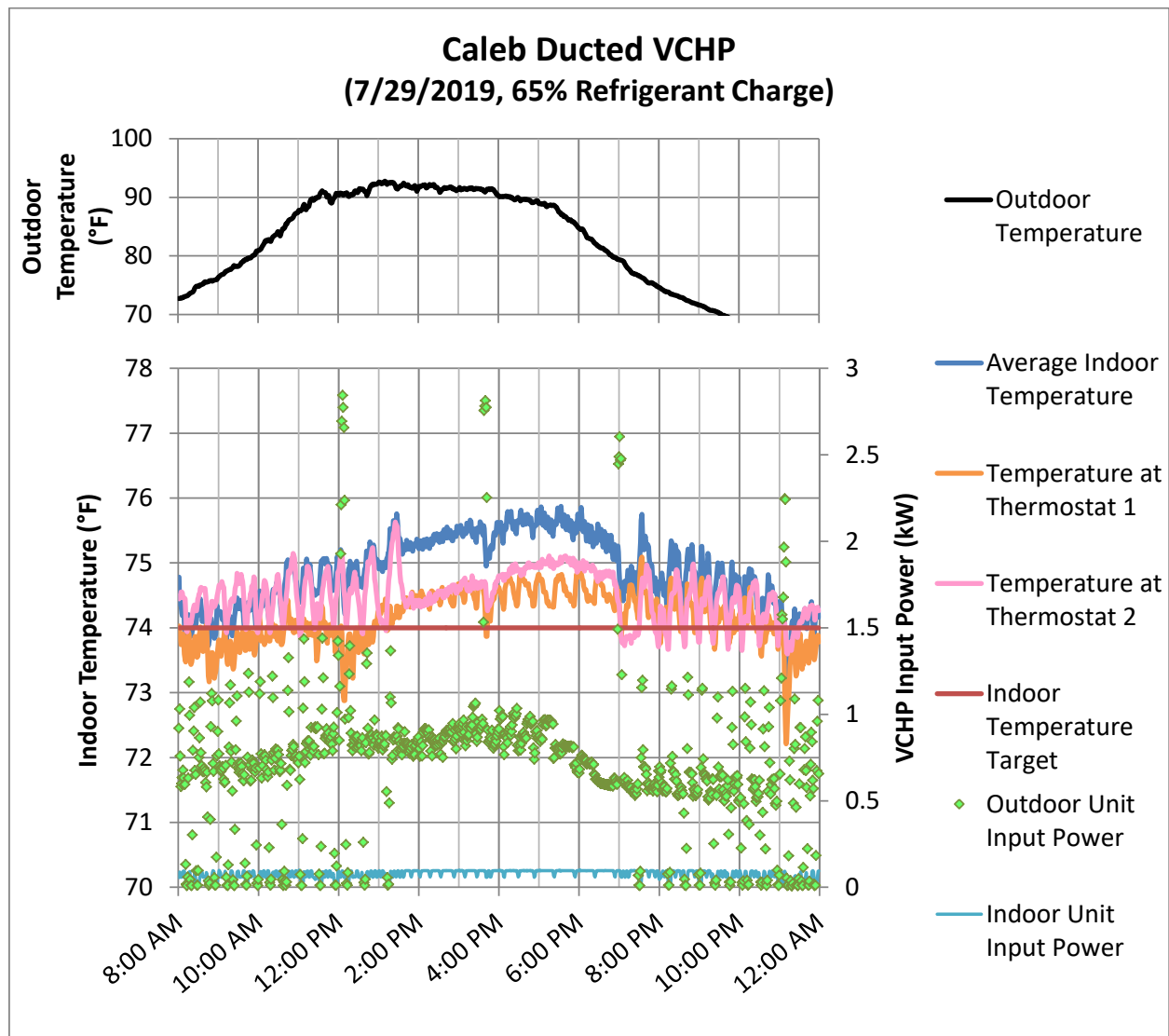


FIGURE 30. CALEB DUCTED VCHP COOLING EXAMPLE, 65% REFRIGERANT CHARGE

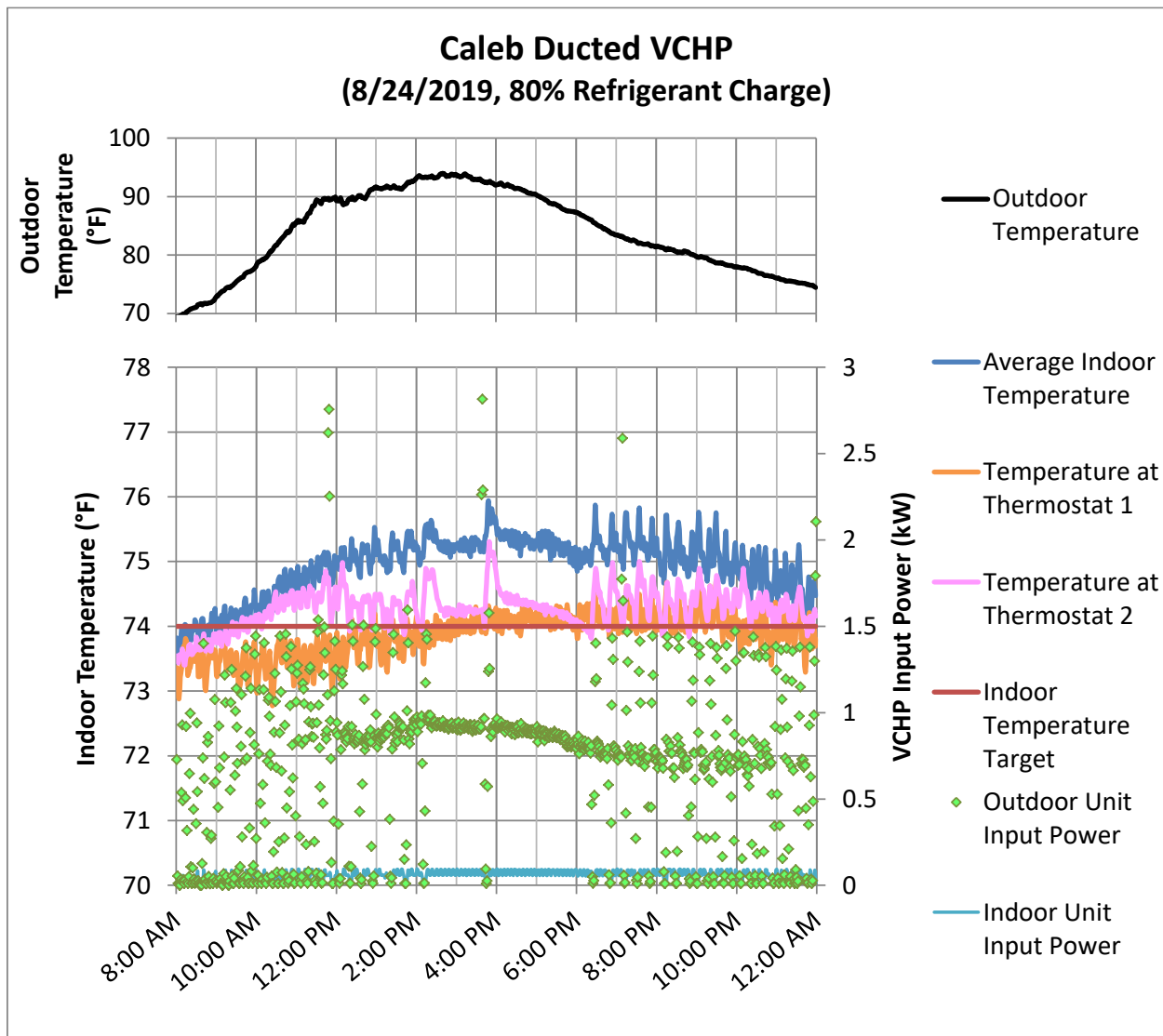


FIGURE 31. CALEB DUCTED VCHP COOLING EXAMPLE, 80% REFRIGERANT CHARGE

The ducted VCHP system malfunctioned on some days at the lowest refrigerant levels. Examples are shown in Figure 32 and Figure 33. In Figure 32 the system stopped operating for about an hour at 2:30 PM. Input power was near zero and indoor temperatures were uncontrolled during this time. A similar malfunction occurred on two other days. In one case the interruption was relatively minor, similar to Figure 32. In the other case the system shut off at 2:45 PM and did not operate for the rest of the day. The days with minor interruptions were included in the daily energy use analysis. The day where indoor temperatures were uncontrolled from 2:45 PM until midnight was not included. Similar malfunctions were not observed at any other refrigerant level during this experiment, or during the prior year when this same VCHP system was monitored for a different experiment.

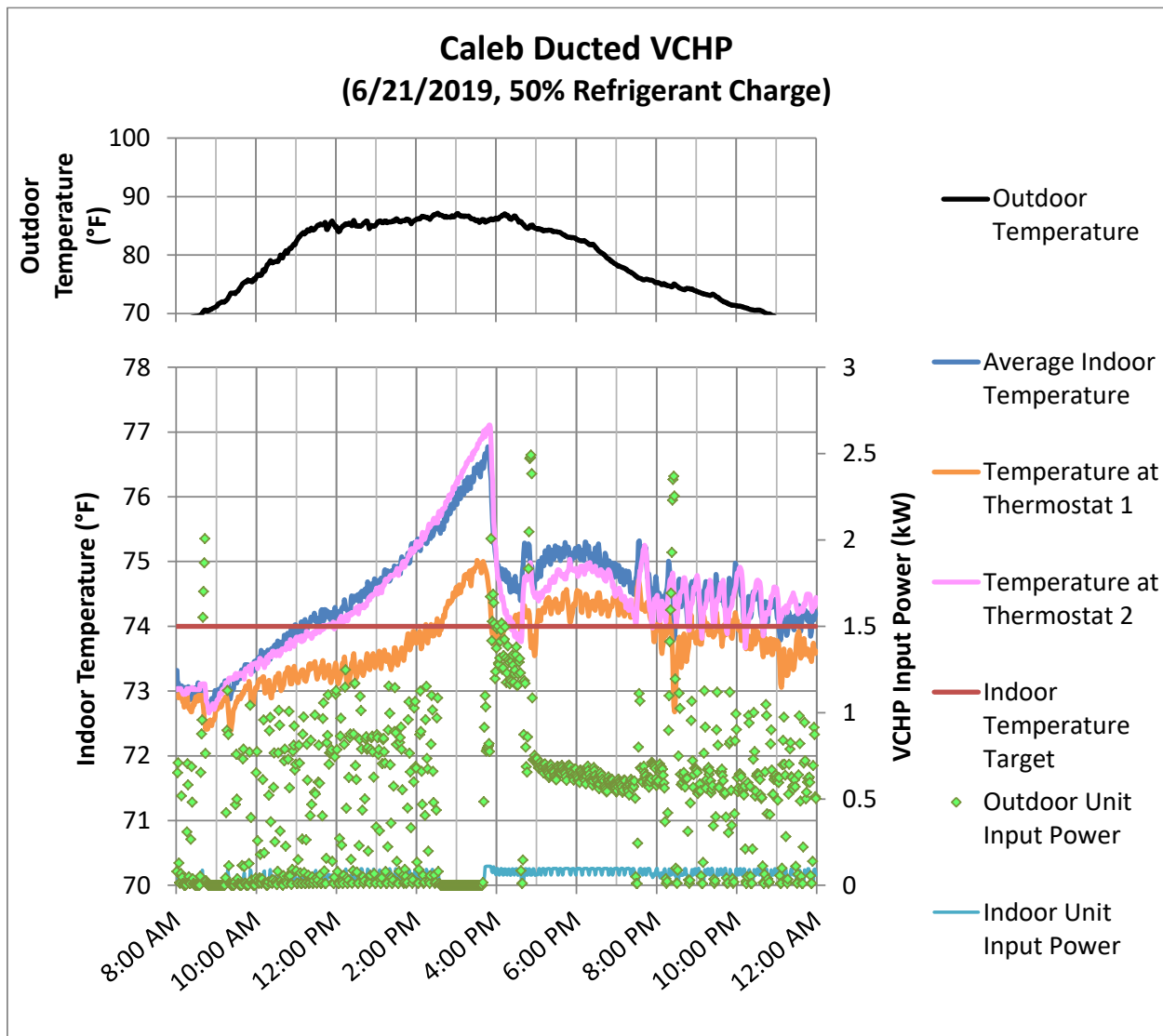


FIGURE 32. CALEB DUCTED VCHP SYSTEM SHUTOFF MALFUNCTION, COOLING MODE

In Figure 33 the system operated for most of the afternoon with no apparent flow of liquid refrigerant to the second floor air handler. The second floor air handler was operating during this time, and input power increased from 50W to about 80W indicating that the system was increasing fan speed, but no cooling was being produced. The air temperature drop across the second floor air handler, as calculated from the room temperature near the return and the average temperature measured at three supply grilles on the second floor, remained near zero all afternoon until the system began operating at a higher compressor speed at about 6:30 PM. Temperature at the second floor thermostat exceeded target by more than 6 °F. This day was excluded from the daily energy use analysis since the malfunction left temperature on the second floor of the house uncontrolled for much of the day.

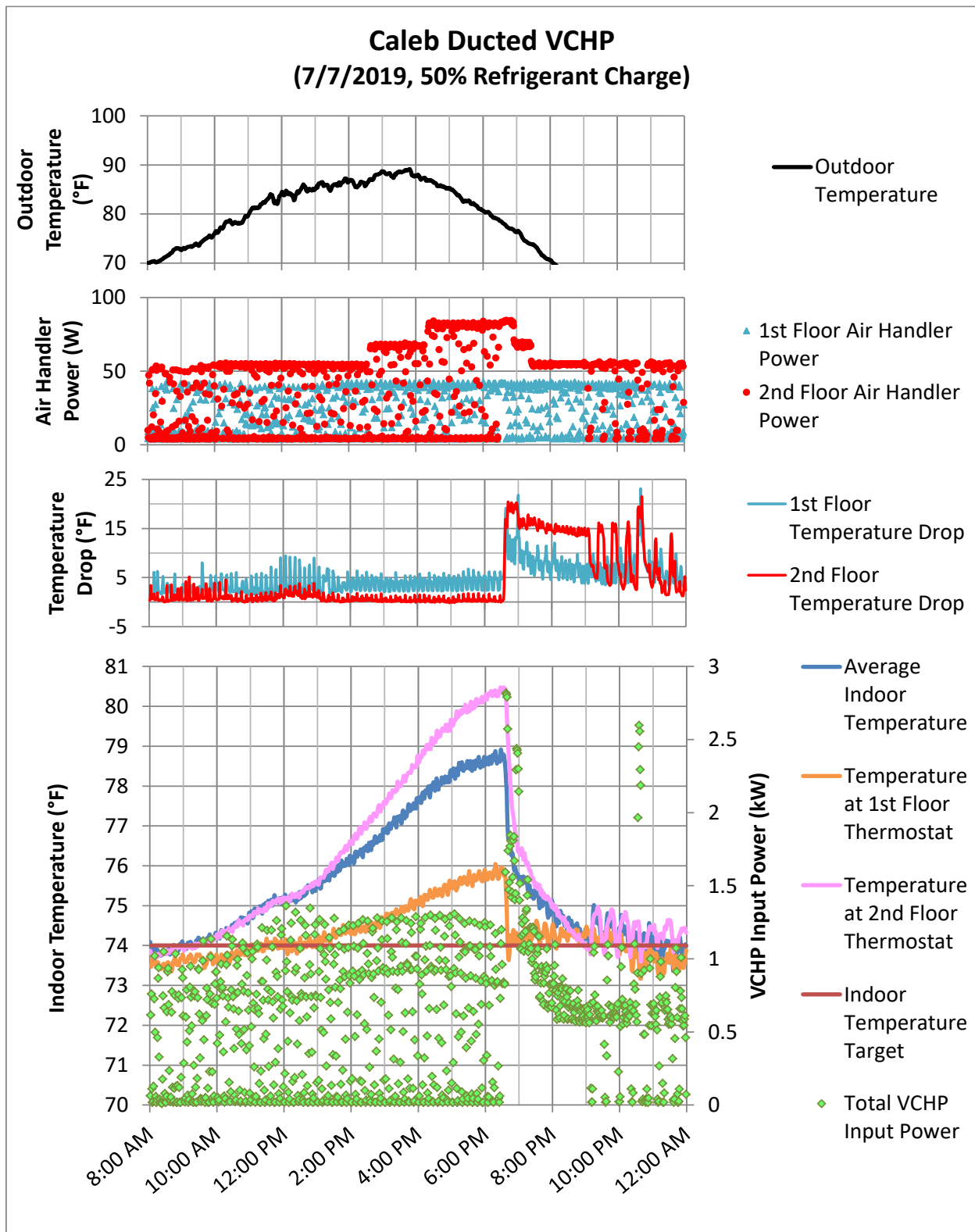


FIGURE 33. CALEB DUCTED VCHP REFRIGERANT FLOW CONTROL MALFUNCTION, COOLING MODE

Figure 34 plots the Ducted VCHP input power against outdoor temperature at each of the four refrigerant levels. The plotted data includes all days the Ducted VCHP system operated during the 2019 cooling season, and each plotted point represents one minute. The large cluster of data points at about 1 kW reflects the system's preferred low speed. Figure 34 shows that this system operated at less than maximum capacity the majority of the time at all refrigerant levels.

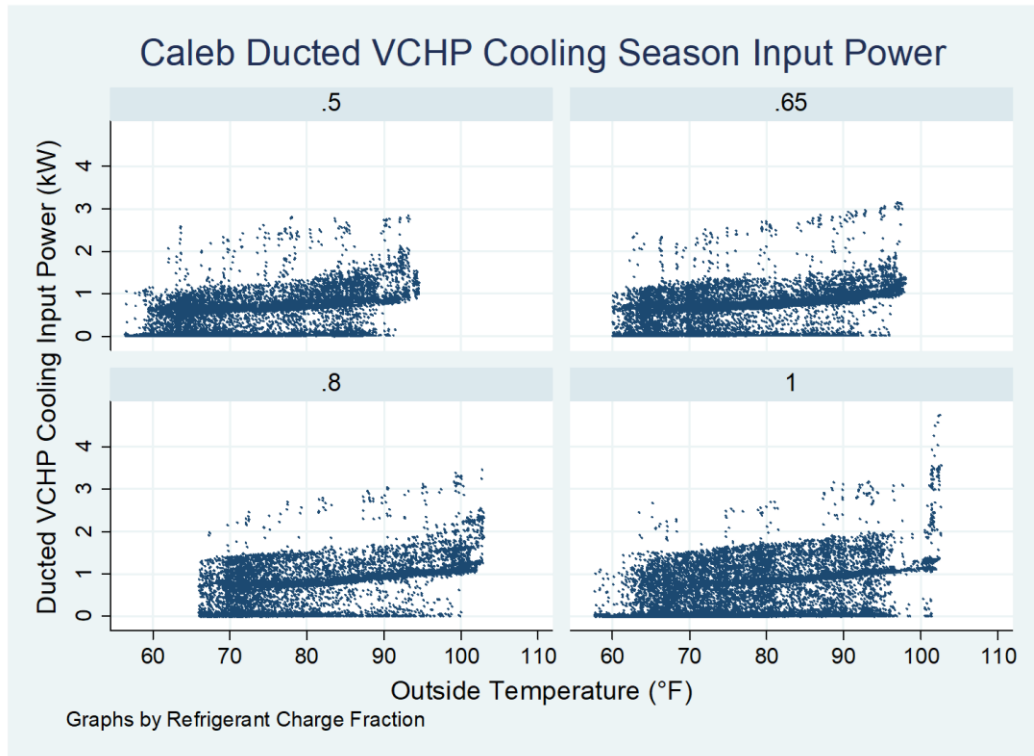


FIGURE 34. CALEB DUCTED VCHP INPUT POWER IN COOLING MODE

Cycling characteristics, defined as compressor on/off transition, for the Ducted VCHP at each refrigerant level are tabulated against daily average outdoor temperature in Table 20. The tabulated temperature values represent the center of a 5 °F temperature bin, and cycling characteristics represent the average of all days within that temperature range. Cells marked with "-" indicate that no days within the temperature bin occurred during monitoring the specified refrigerant level. This system typically runs a large number of short cycles, exceeding 140 cycles per day on mild days. Low refrigerant charge increased the average cycle length and decreased the number of cycles per day.

TABLE 20. CALEB DUCTED VCHP CYCLING CHARACTERISTICS IN COOLING MODE

	DAILY AVERAGE OUTDOOR TEMPERATURE (°F)	50%	REFRIGERANT LEVEL		
			65%	80%	100%
Average Cycle Length (Minutes)	70	6.3	6.1	-	3.0
	75	7.8	10.0	-	4.3
	80	-	15.6	9.3	6.2
	85	-	-	13.2	11.0
Average Cycles Per Day	70	106.3	134.0	-	119.0
	75	86.8	96.0	-	146.3
	80	-	56.0	107.5	124.2
	85	-	-	83.7	98.0

DAILY ENERGY USE

The daily cooling energy use regression results for the Ducted VCHP are shown in Table 21. Figure 35 displays the monitored and regression predicted daily energy use for each refrigerant level. Figure 36 displays the monitored and regression predicted VCHP daily energy use plotted against daily average outdoor temperature, comparing the modeled results to directly monitored data.

TABLE 21. CALEB DUCTED VCHP DAILY COOLING ENERGY REGRESSION

SYSTEM	VARIABLE	COEFFICIENT	t	95% CONFIDENCE INTERVAL	
Ducted VCHP	E _{Ref}	0.8092	13.92	0.6905	0.9280
	E _{Ref_R50}	0.3216	5.48	0.2018	0.4414
	E _{Ref_R65}	0.1873	4.53	0.1029	0.2717
	E _{Ref_R80}	0.0741	1.86	-0.0072	0.1554
	Constant	1.9020	2.53	0.3637	3.4404
	R ²	0.92			
	Daily Standby kWh	0.57			

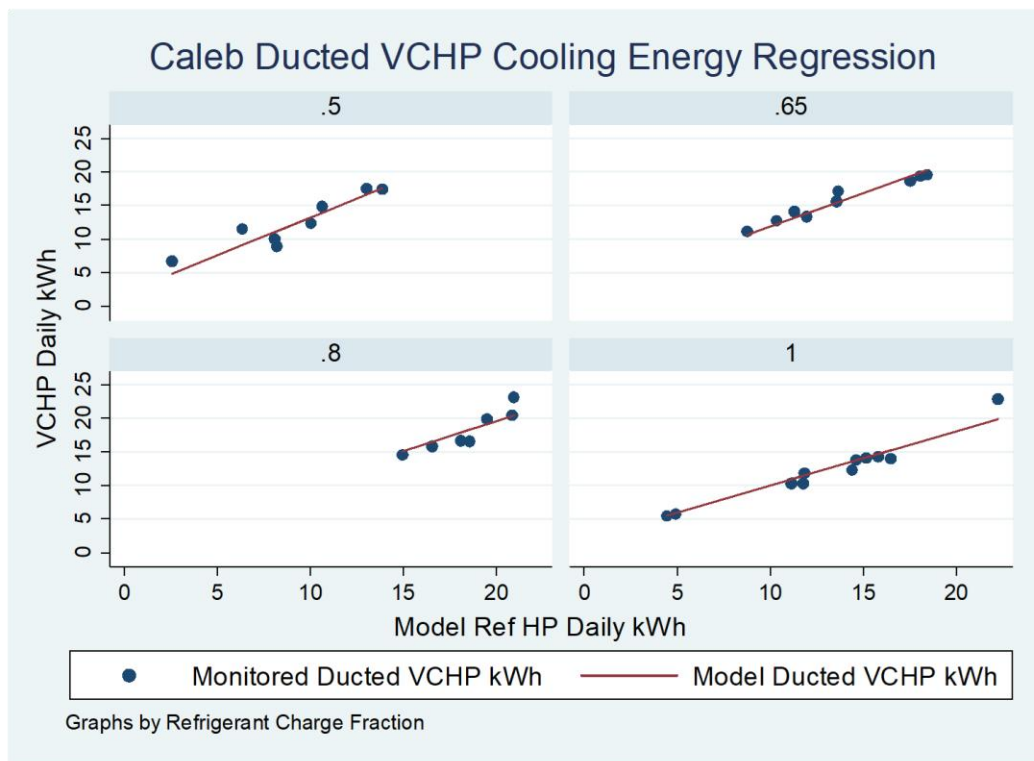


FIGURE 35. CALEB DUCTED VCHP DAILY COOLING ENERGY REGRESSION

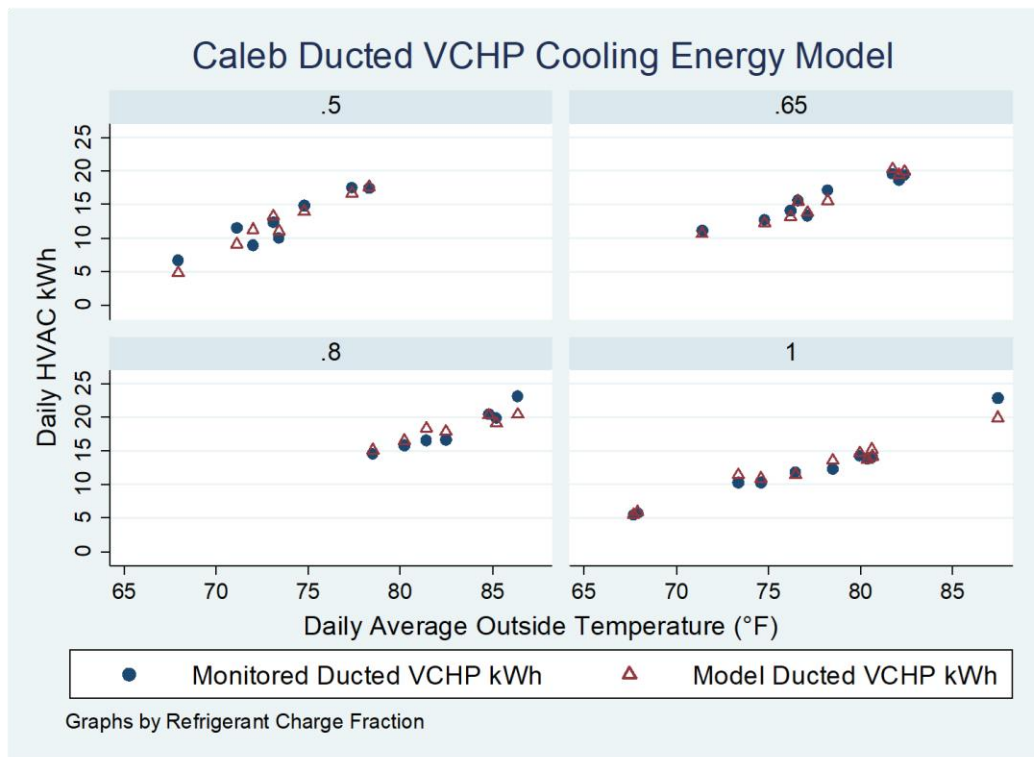


FIGURE 36. CALEB DUCTED VCHP MONITORED AND MODEL PREDICTED DAILY COOLING ENERGY

The regression predicted normalized seasonal energy use estimates are shown in Table 22. The daily energy use analysis shows efficiency reductions at all three refrigerant undercharge levels, with a loss of 23% at 50% refrigerant charge. The implied efficiency representation presumes that an identical amount of cooling was provided in each case.

TABLE 22. CALEB DUCTED VCHP NORMALIZED COOLING SEASON ENERGY USE

SYSTEM	REFRIGERANT LEVEL	SEASONAL ENERGY USE (kWh)	SEASONAL ENERGY USE RELATIVE TO CORRECT REFRIGERANT CHARGE	IMPLIED EFFICIENCY RELATIVE TO CORRECT REFRIGERANT CHARGE
Ducted VCHP	50%	1947.1	130%	77%
	65%	1761.0	117%	85%
	80%	1604.2	107%	94%
	100%	1501.5	100%	100%

AFTERNOON AND EVENING DEMAND

Refrigerant undercharge increased evening demand of the Ducted VCHP. Demand was increased by as much as 70% during some evening hours at 50% refrigerant charge. Impacts were smaller at 65% and 80% refrigerant charge. Average hourly demand relative to performance at correct refrigerant charge is tabulated in Table 23. The tabulated temperature values represent the center of a 5 °F temperature bin, and demand characteristics represent the average of all hours within that temperature range. The monitored energy use during each hour for each refrigerant level is plotted in Figure 37.

TABLE 23. CALEB DUCTED VCHP AVERAGE HOURLY DEMAND RELATIVE TO PERFORMANCE AT CORRECT REFRIGERANT CHARGE

REFRIGERANT LEVEL	HOUR	HOURLY AVERAGE OUTDOOR TEMPERATURE (°F)				
		80	85	90	95	100
50%	2-3 PM	103%	75%	108%	111%	-
	3-4 PM	94%	72%	90%	109%	-
	4-5 PM	104%	90%	110%	140%	-
	5-6 PM	109%	111%	169%	-	-
	6-7 PM	126%	172%	151%	-	-
	7-8 PM	135%	137%	-	-	-
	8-9 PM	128%	-	-	-	-
	9-10 PM	-	-	-	-	-
65%	2-3 PM	-	102%	106%	120%	-
	3-4 PM	-	92%	125%	114%	-
	4-5 PM	129%	-	101%	133%	-
	5-6 PM	-	122%	110%	128%	-
	6-7 PM	99%	104%	117%	-	-
	7-8 PM	110%	121%	-	-	-
	8-9 PM	101%	99%	-	-	-
	9-10 PM	96%	-	-	-	-
80%	2-3 PM	-	-	-	108%	46%
	3-4 PM	-	-	-	102%	73%
	4-5 PM	-	-	99%	97%	101%
	5-6 PM	-	-	107%	91%	-
	6-7 PM	-	104%	117%	-	-
	7-8 PM	111%	113%	-	-	-
	8-9 PM	102%	93%	-	-	-
	9-10 PM	107%	-	-	-	-

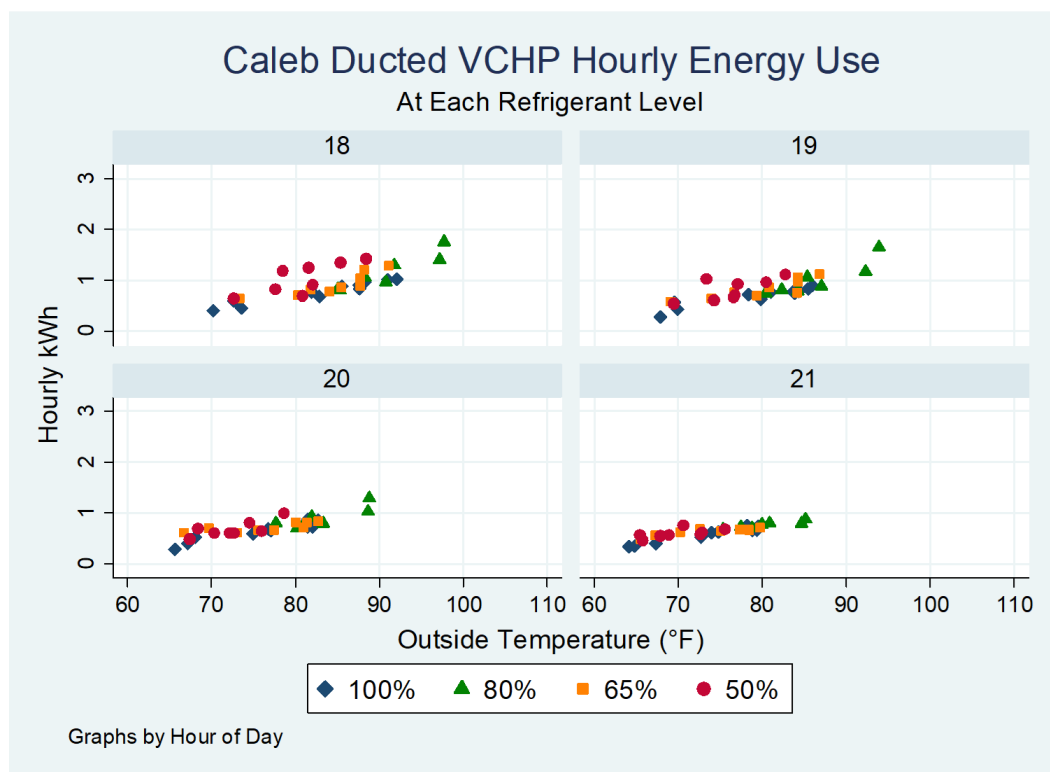
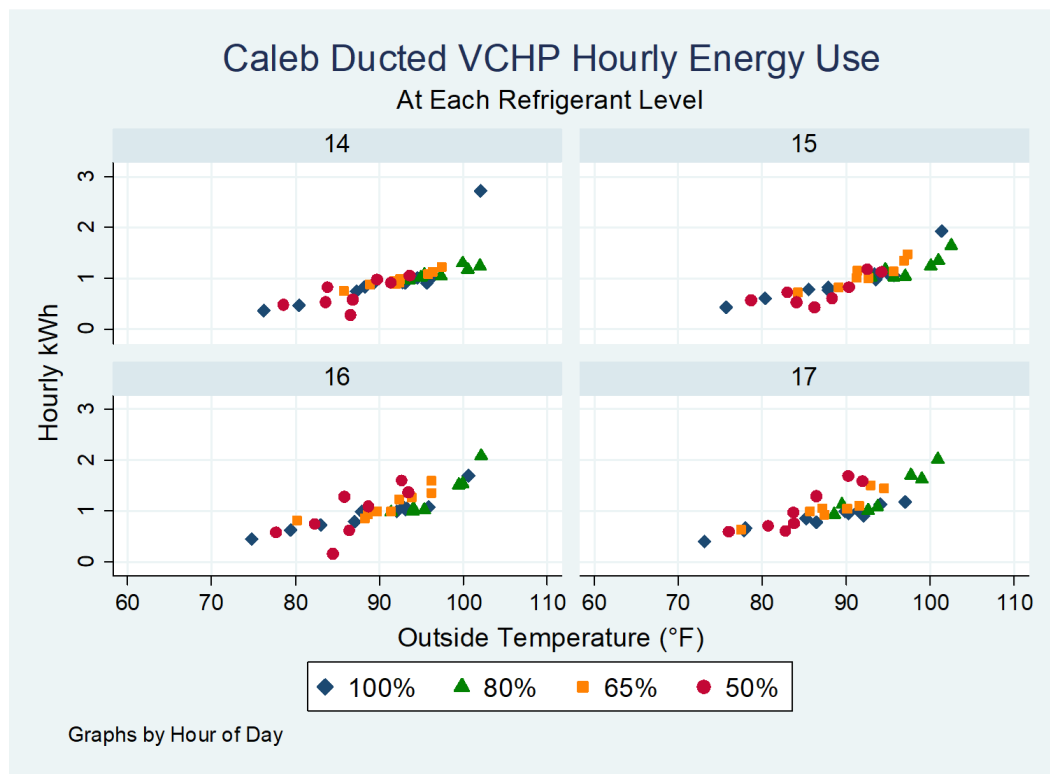


FIGURE 37. CALEB DUCTED VCHP COOLING SEASON HOURLY ENERGY USE AT EACH REFRIGERANT LEVEL

HEATING SEASON

The Ducted VCHP system maintained similar indoor temperatures at all refrigerant levels. There are some small differences at the warmest outdoor conditions. Average temperatures of each room relative to the target temperature are shown in Figure 38. Average indoor temperatures relative to the temperatures at correct refrigerant charge are shown in Figure 39. The plotted values represent the average of all minutes that occurred during hours with compressor operation during the hour, indicating that the system was providing heating to the house during the hour. The first floor of this house (living room and kitchen) is controlled by a thermostat located in the living room, and the second floor (landing and bedrooms) is controlled by a thermostat located in the landing.

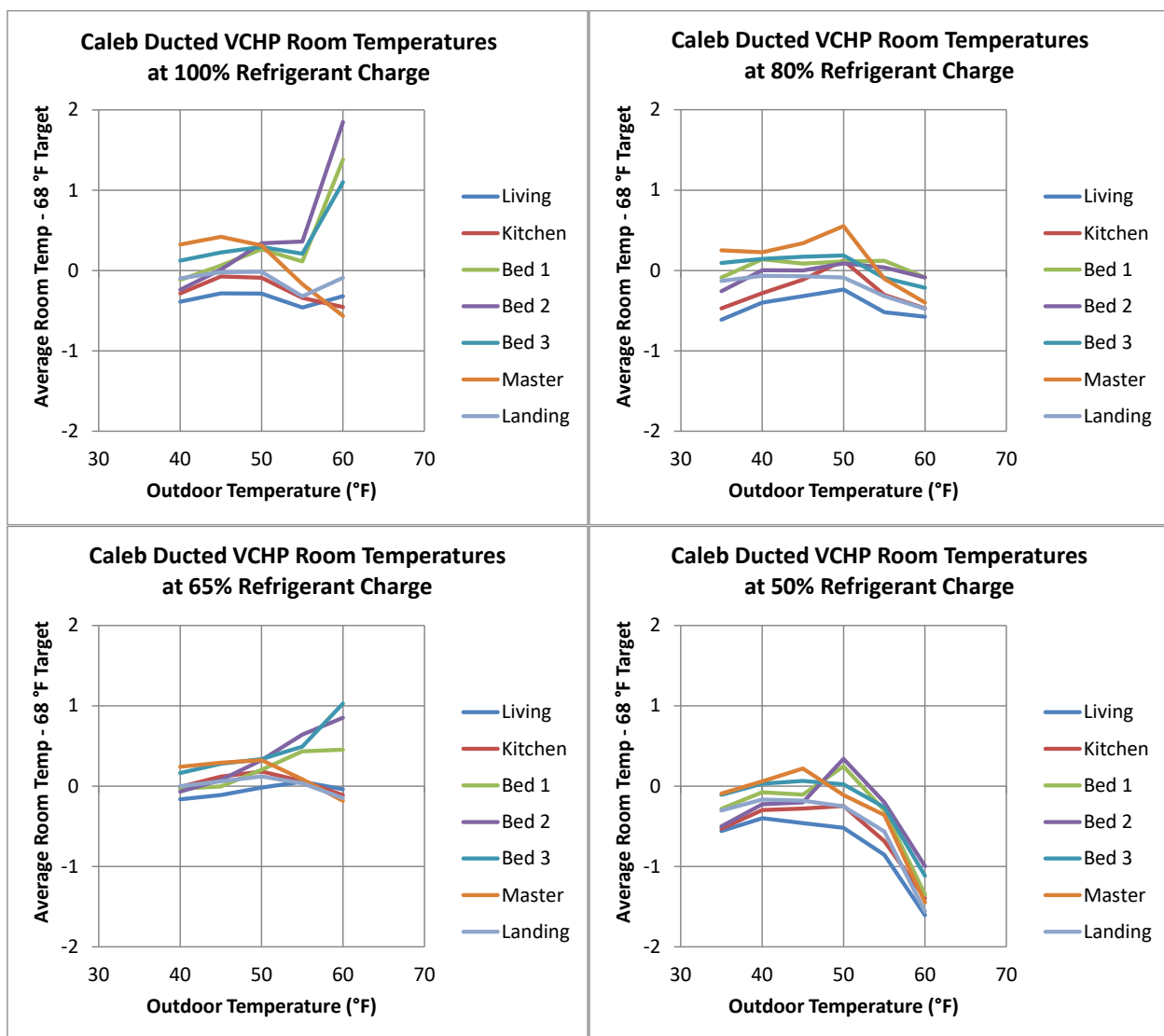


FIGURE 38. CALEB DUCTED VCHP HEATING SEASON INDOOR TEMPERATURE DELTA TO TARGET

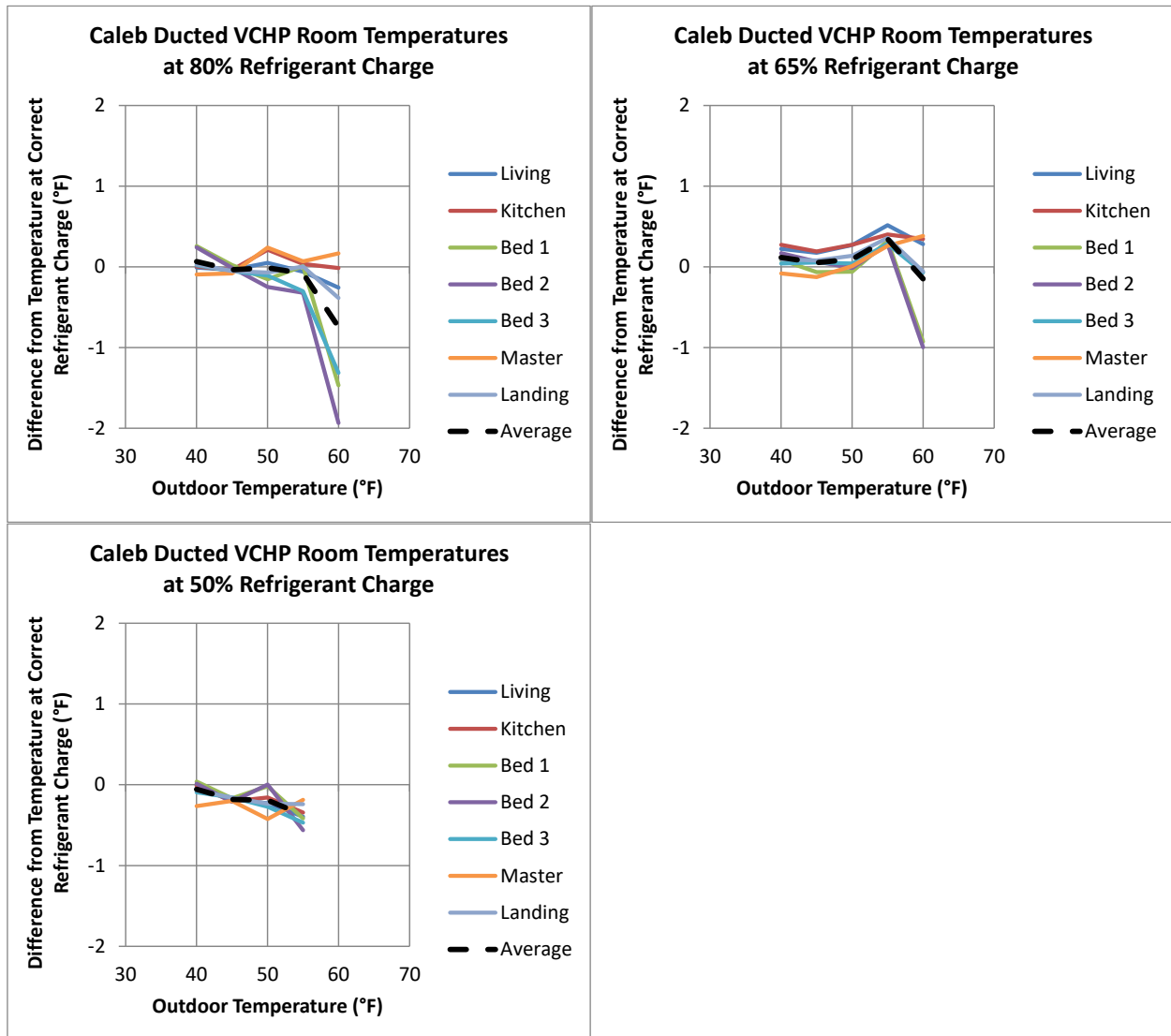


FIGURE 39. CALEB DUCTED VCHP HEATING SEASON INDOOR TEMPERATURES AT REFRIGERANT UNDERCHARGE CONDITIONS RELATIVE TO TEMPERATURES AT CORRECT REFRIGERANT CHARGE

Figure 40 and Figure 41 show examples of how this system operated on days with similar outdoor temperature at correct refrigerant charge and at 50% refrigerant charge. Each plotted point represents one minute. The system ran short and frequent cycles on both days.

Defrost cycles did not occur on these days. Defrost operation was infrequent, with only three defrost cycles observed during the winter.

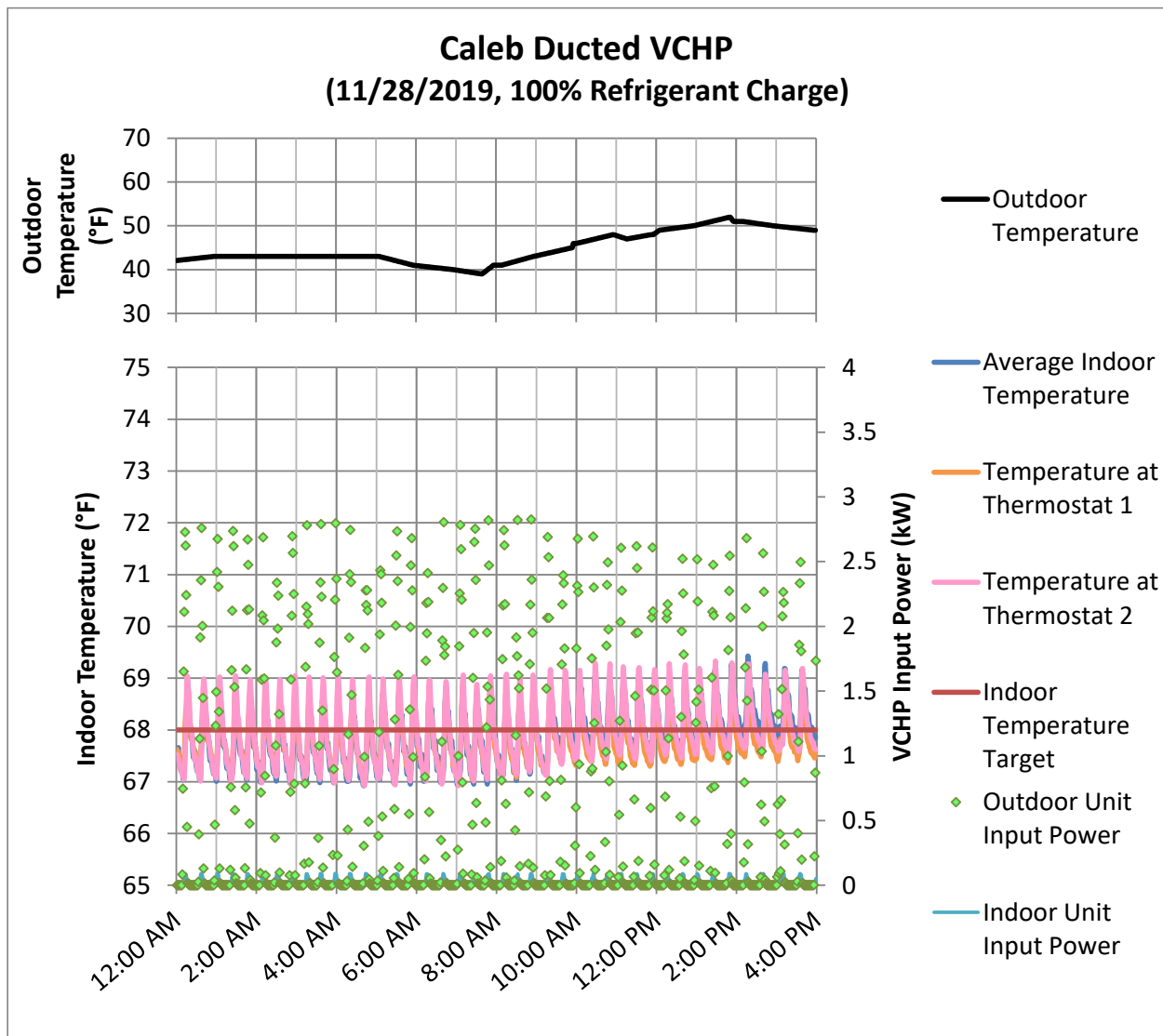


FIGURE 40. CALEB DUCTED VCHP HEATING EXAMPLE, CORRECT REFRIGERANT CHARGE

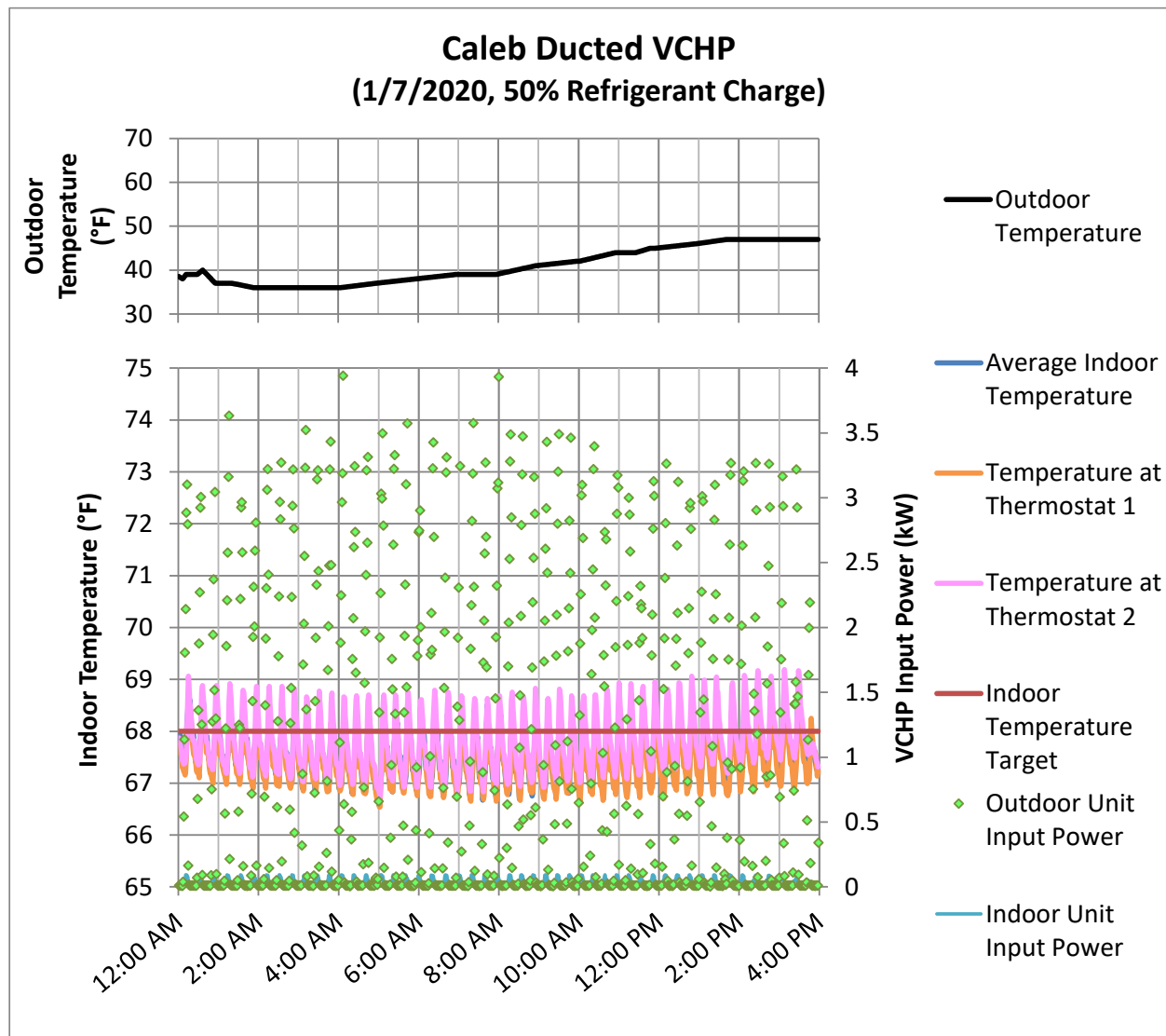


FIGURE 41. CALEB DUCTED VCHP HEATING EXAMPLE, 50% REFRIGERANT CHARGE

Figure 42 and Figure 43 show days at 65% and 80% refrigerant charge. The 65% day is warmer due to mild weather throughout the 65% testing period.

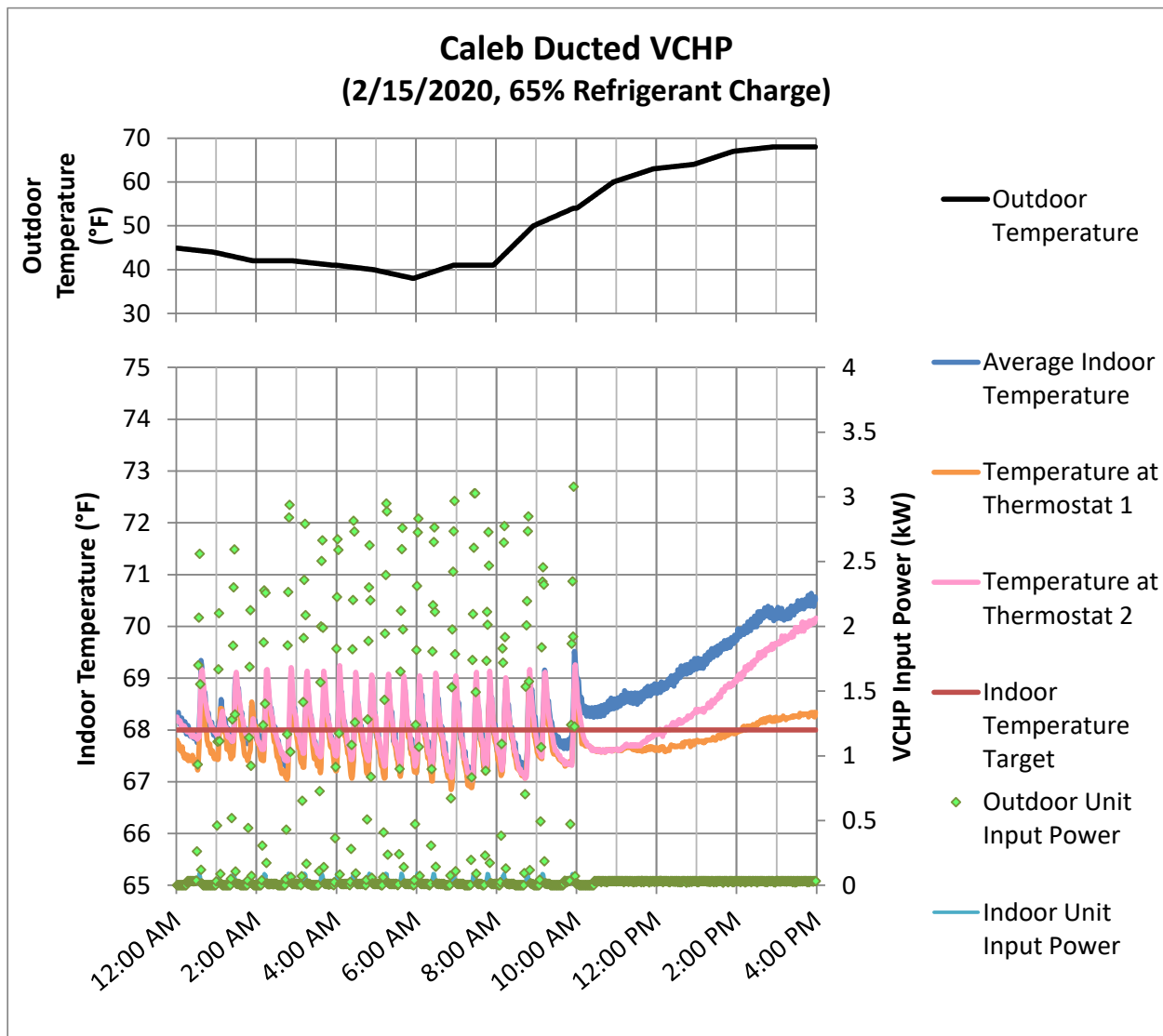


FIGURE 42. CALEB DUCTED VCHP HEATING EXAMPLE, 65% REFRIGERANT CHARGE

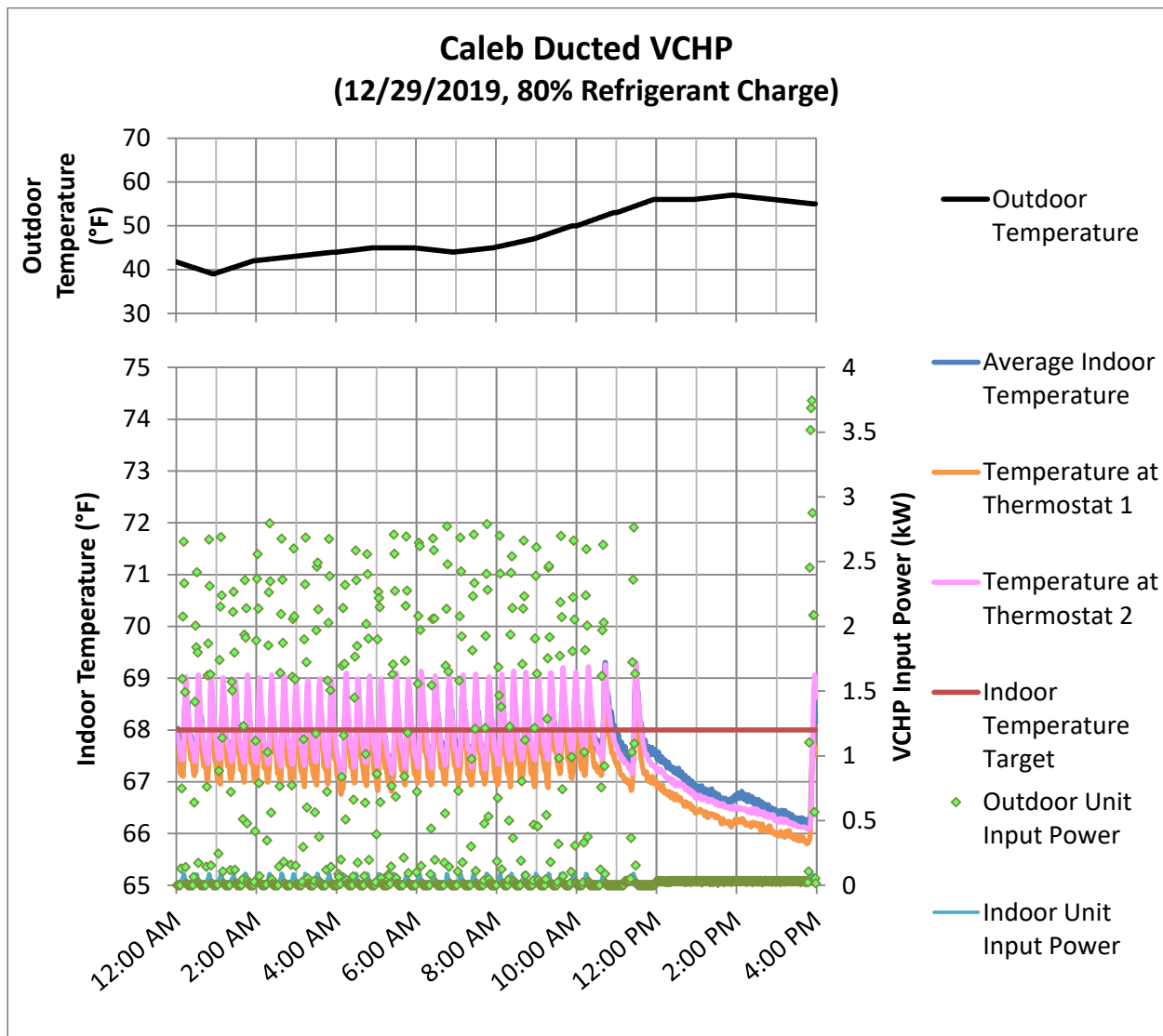


FIGURE 43. CALEB DUCTED VCHP HEATING EXAMPLE, 80% REFRIGERANT CHARGE

Figure 44 plots the Ducted VCHP input power against outdoor temperature at each of the four refrigerant levels. The plotted data includes all days the Ducted VCHP system operated during the 2019-2020 heating season, and each plotted point represents one minute. Maximum one minute input power tended to be higher at low refrigerant levels than at correct refrigerant charge, but in all cases the unit was cycling and not running continuously.

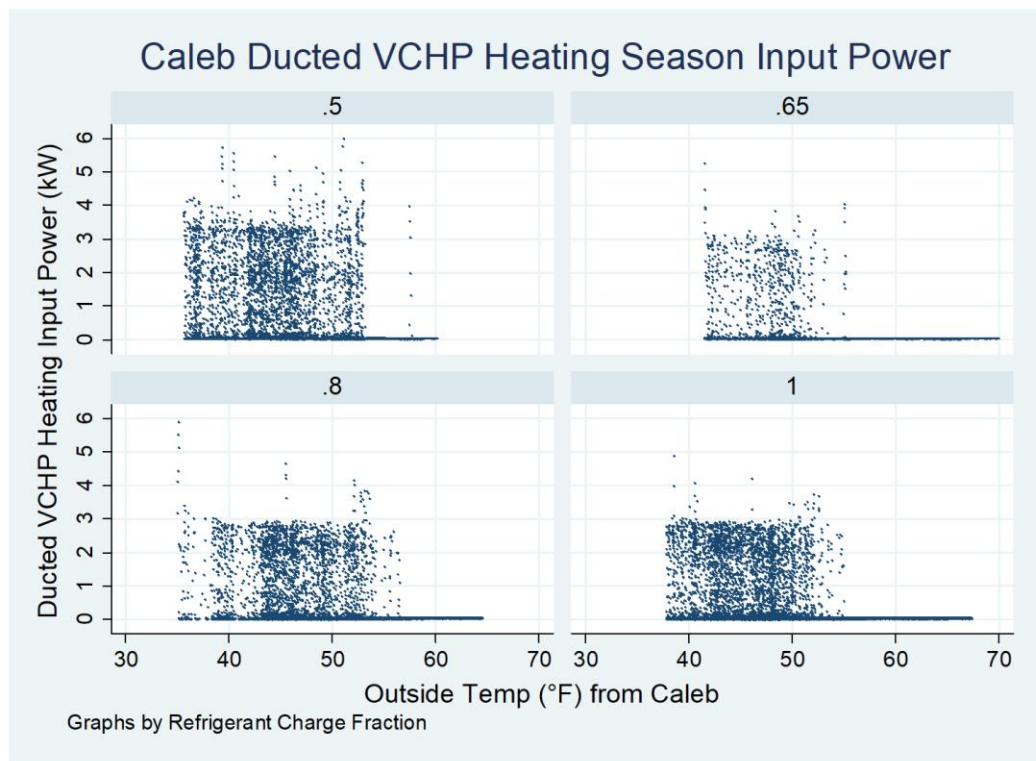


FIGURE 44. CALEB DUCTED VCHP INPUT POWER IN HEATING MODE

Cycling characteristics for the Ducted VCHP at each refrigerant level are tabulated against daily average outdoor temperature in Table 24. Refrigerant levels had little impact on cycling behavior. Cycle length increased slightly at the lowest refrigerant level.

TABLE 24. CALEB DUCTED VCHP CYCLING CHARACTERISTICS IN HEATING MODE

	DAILY AVERAGE OUTDOOR TEMPERATURE (°F)	REFRIGERANT LEVEL			
		50%	65%	80%	100%
Average Cycle Length (Minutes)	45	7.2	-	6.3	6.8
	50	7.5	6.7	6.4	6.1
	55	8.0	6.3	7.5	6.5
	60	-	6.5	5.7	6.4
Average Cycles Per Day	45	52.5	-	46.0	55.0
	50	26.3	26.0	38.6	34.0
	55	18.0	11.0	6.0	20.8
	60	-	2.3	2.0	5.0

DAILY ENERGY USE

The daily heating energy use regression results for the Ducted VCHP are shown in Table 25. Figure 45 displays the monitored and regression predicted daily energy use for each refrigerant level. Figure 46 displays the monitored and regression predicted VCHP daily energy use plotted against daily average outdoor temperature, comparing the modeled results to directly monitored data.

TABLE 25. CALEB DUCTED VCHP DAILY HEATING ENERGY REGRESSION

SYSTEM	VARIABLE	COEFFICIENT	t	95% CONFIDENCE INTERVAL	
Ducted VCHP	E _{Ref}	0.2688	13.44	0.2283	0.3093
	E _{Ref_R50}	0.0398	2.35	0.0055	0.0742
	E _{Ref_R65}	-0.0296	-0.86	-0.0993	0.0400
	E _{Ref_R80}	0.0095	0.49	-0.0294	0.0485
	Constant	-0.0229	-0.06	-0.8586	0.8128
	R ²	0.91			
	Daily Standby kWh	0.96			

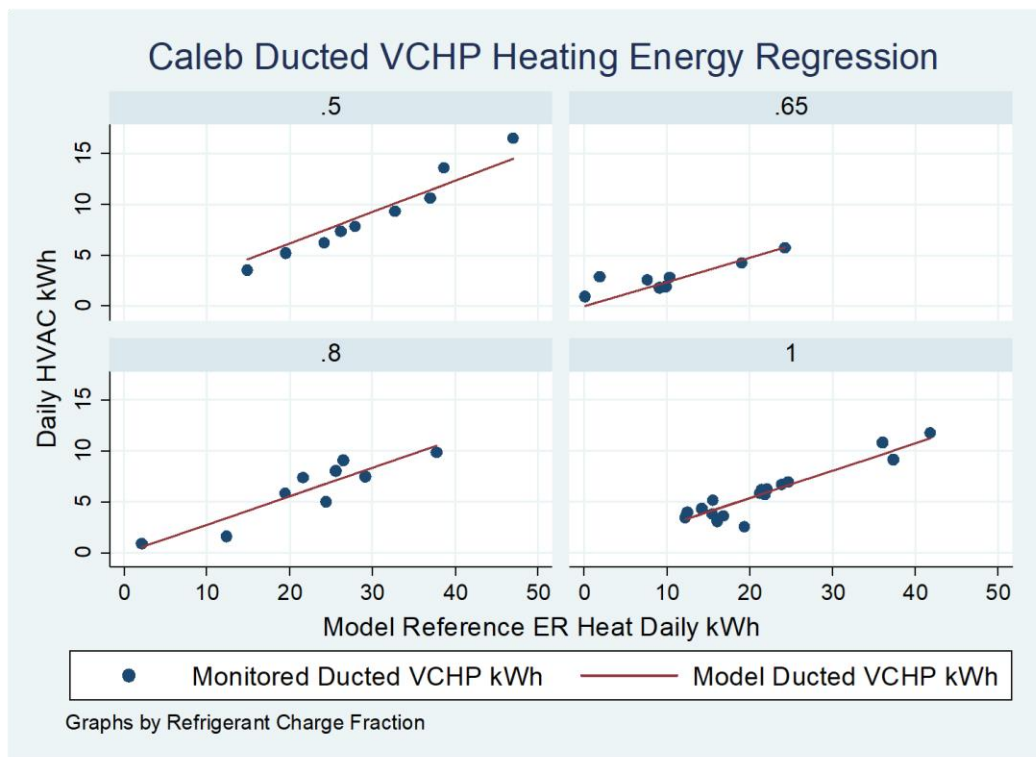


FIGURE 45. CALEB DUCTED VCHP DAILY HEATING ENERGY REGRESSION

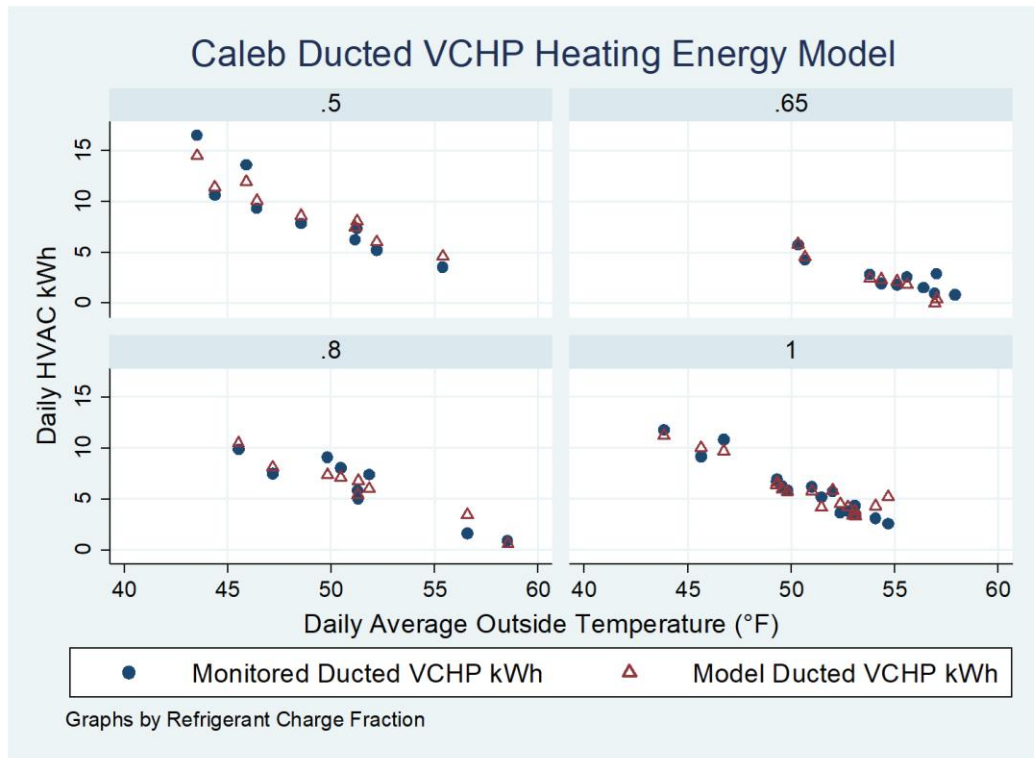


FIGURE 46. CALEB DUCTED VCHP MONITORED AND MODEL PREDICTED DAILY HEATING ENERGY

The regression predicted normalized seasonal energy use estimates are shown in Table 26. The daily energy use analysis shows an efficiency reduction at 50% refrigerant charge but little or no loss at lower undercharge levels. The 65% monitoring period was limited by warm weather and low heating loads, and should therefore be treated as an incomplete data point. The apparent efficiency gain does not represent performance at typical heating loads.

TABLE 26. CALEB DUCTED VCHP NORMALIZED HEATING SEASON ENERGY USE

SYSTEM	REFRIGERANT LEVEL	SEASONAL ENERGY USE (kWh)	SEASONAL ENERGY USE RELATIVE TO CORRECT REFRIGERANT CHARGE	IMPLIED EFFICIENCY RELATIVE TO CORRECT REFRIGERANT CHARGE
Ducted VCHP	50%	1491.4	113%	88%
	65%	1190.6	90%	111%
	80%	1360.1	103%	97%
	100%	1318.9	100%	100%

CALEB HOUSE, DUCTLESS VCHP

COOLING SEASON

The Ductless VCHP system maintained similar indoor temperatures at all refrigerant levels. Average temperatures of each room relative to the target temperature are shown in Figure 47. Average indoor temperatures relative to the temperatures at correct refrigerant charge are shown in Figure 48. The plotted values represent the average of all minutes that occurred during hours with compressor operation during the hour, indicating that the system was providing cooling to the house during the hour. This system is controlled by thermostats located in each room.

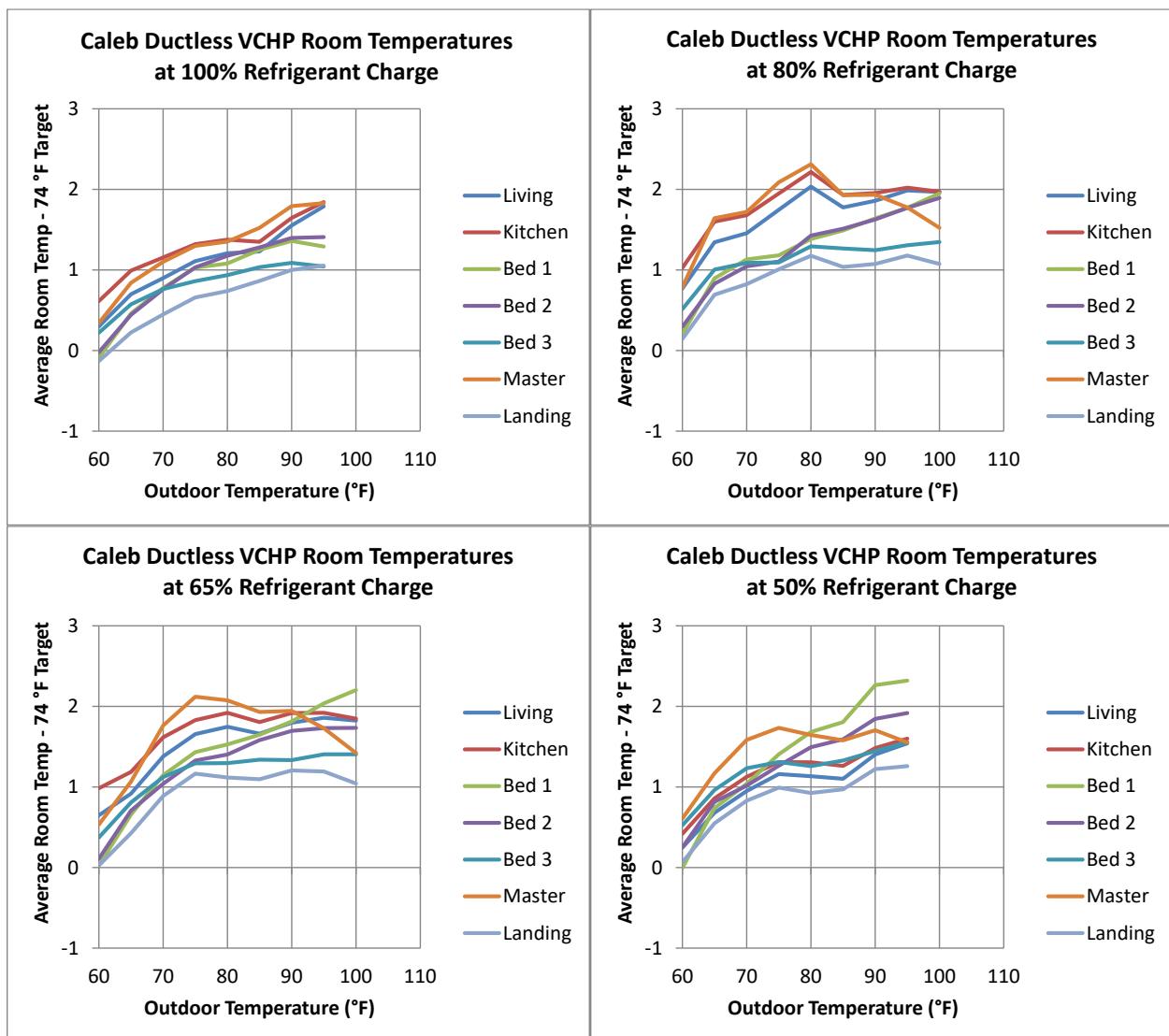


FIGURE 47. CALEB DUCTLESS VCHP COOLING SEASON INDOOR TEMPERATURE DELTA TO TARGET

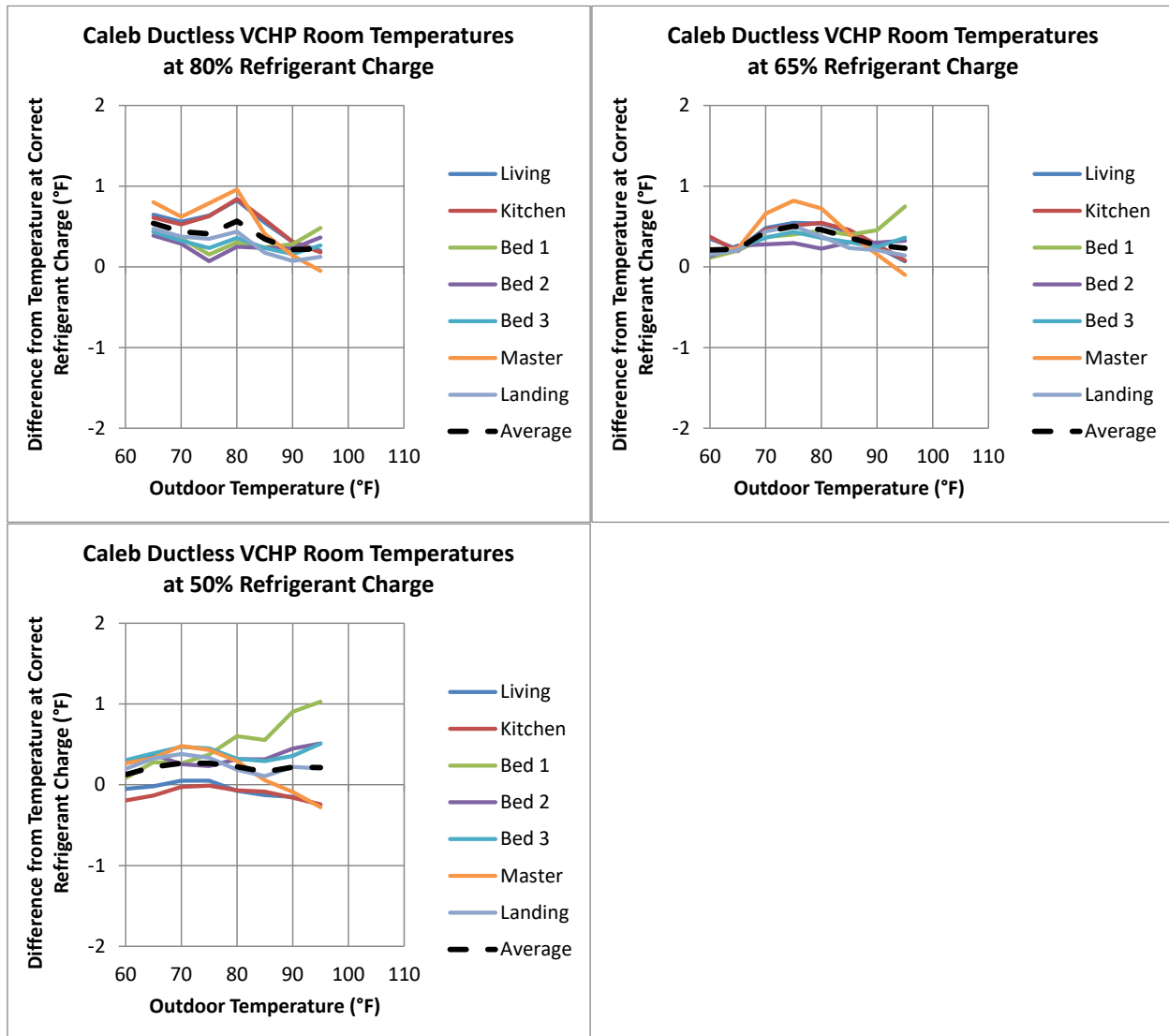
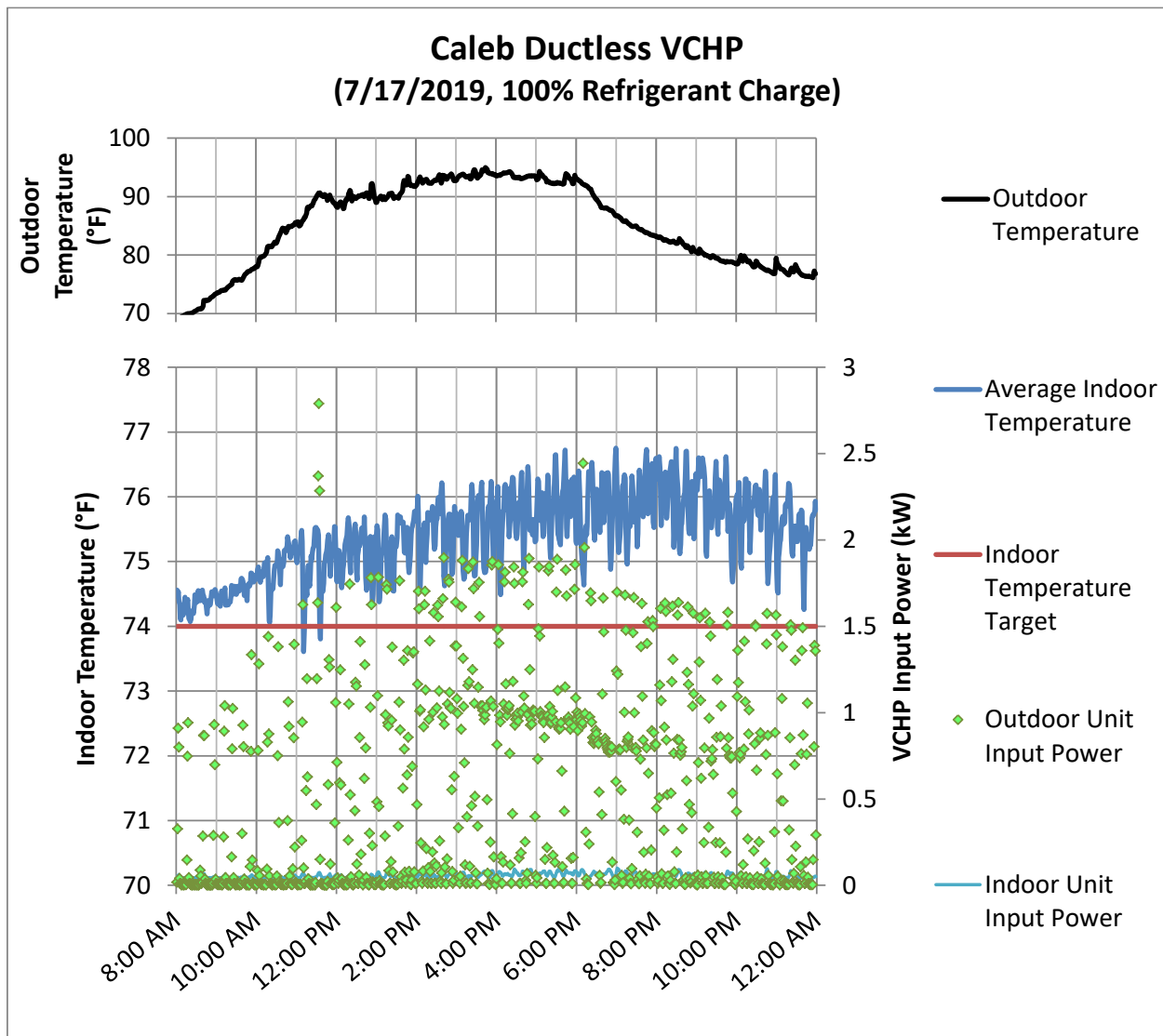


FIGURE 48. CALEB DUCTLESS VCHP COOLING SEASON INDOOR TEMPERATURES AT REFRIGERANT UNDERCHARGE CONDITIONS RELATIVE TO TEMPERATURES AT CORRECT REFRIGERANT CHARGE

Figure 49 and Figure 50 show examples of how this system operated on days with similar outdoor temperature at correct refrigerant charge and at 50% refrigerant charge. Each plotted point represents one minute.

In the morning of both days, when outdoor temperatures were mild and cooling loads were low, the system cycled. At correct refrigerant charge it continued cycling all day. At 50% refrigerant charge it operated continuously throughout much of the afternoon, and operated at higher compressor speeds more frequently than at correct charge.

**FIGURE 49. CALEB DUCTLESS VCHP COOLING EXAMPLE, CORRECT REFRIGERANT CHARGE**

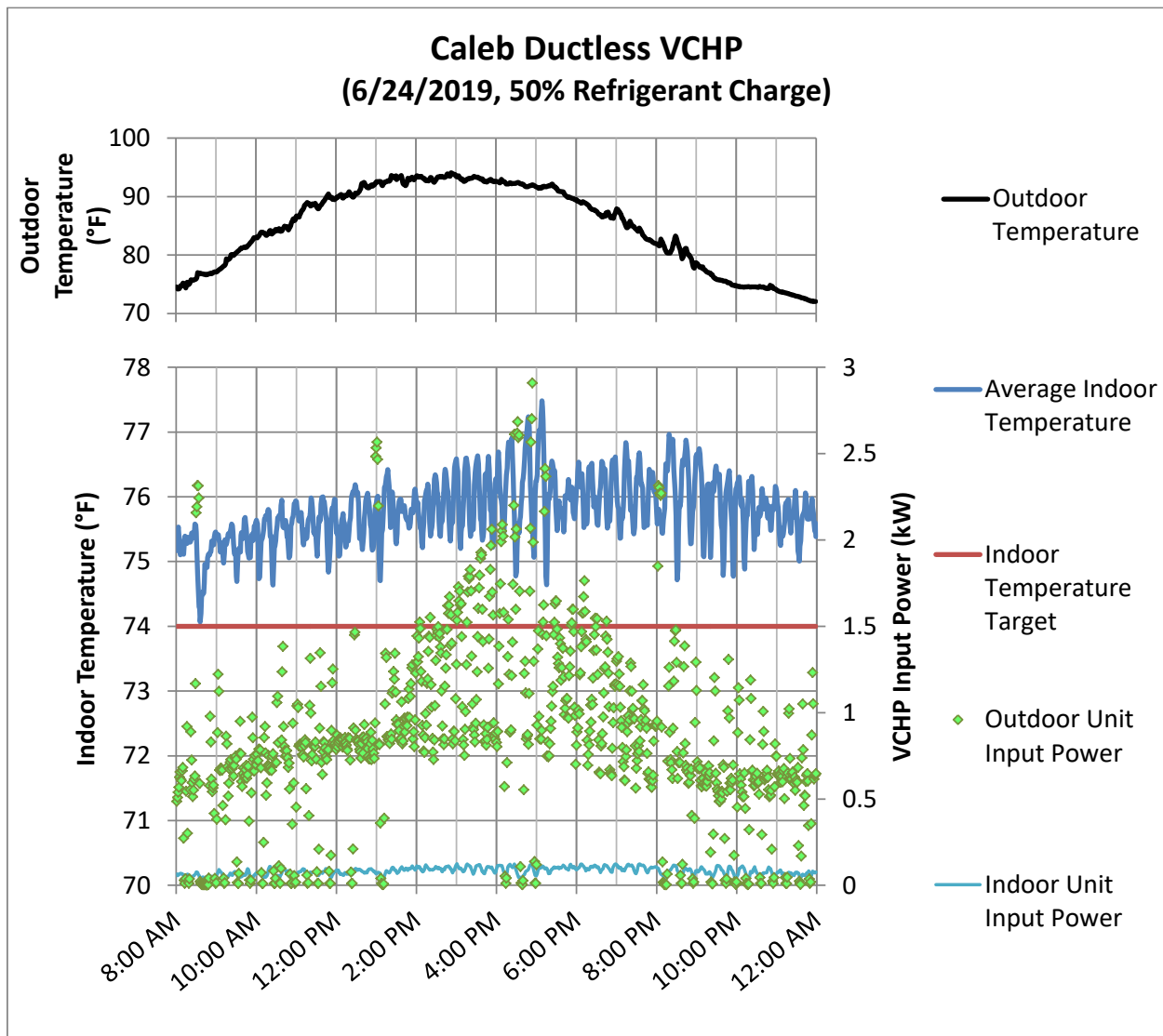


FIGURE 50. CALEB DUCTLESS VCHP COOLING EXAMPLE, 50% REFRIGERANT CHARGE

Figure 51 and Figure 52 show similar days with 65% and 80% refrigerant charge.

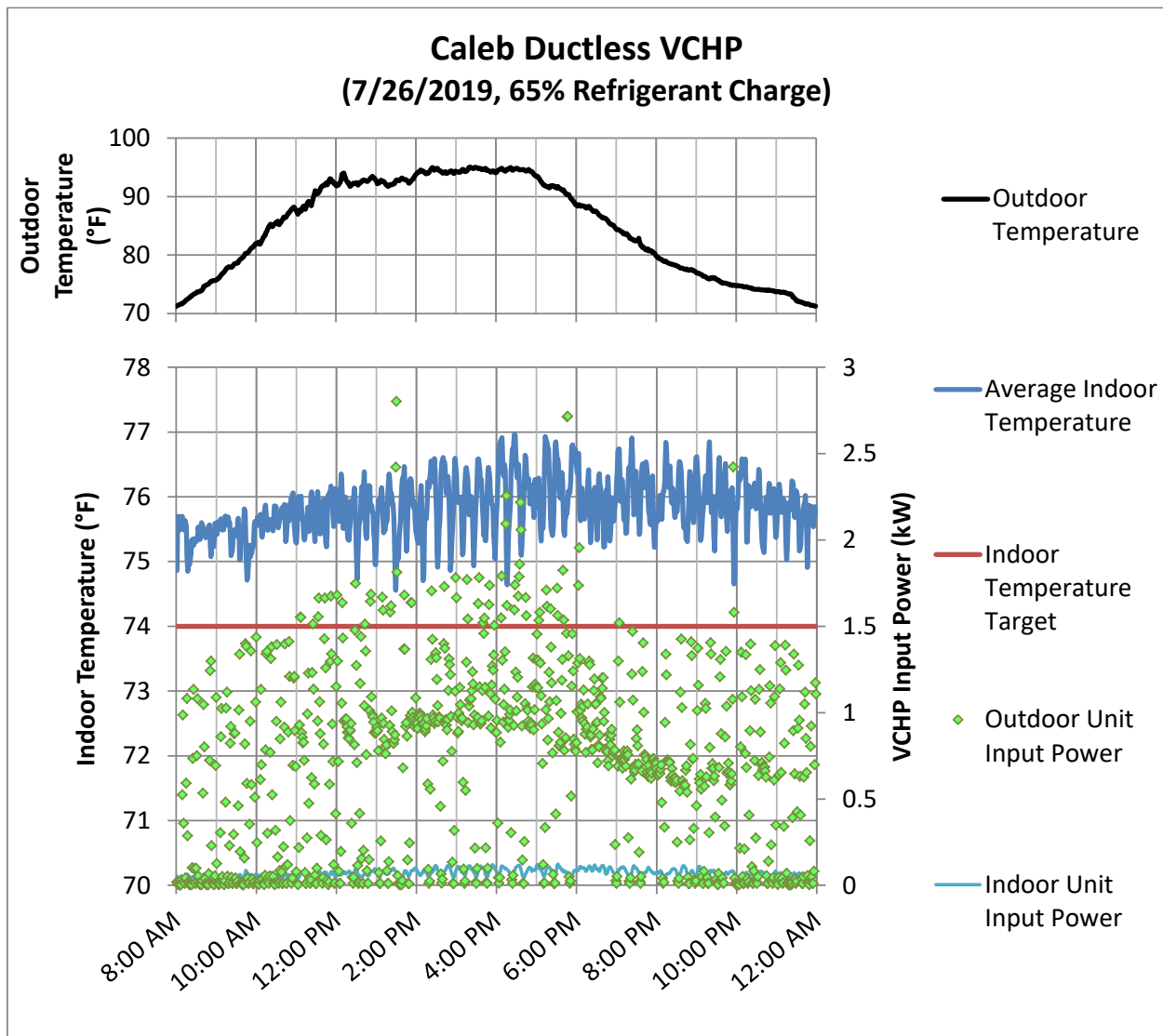


FIGURE 51. CALEB DUCTLESS VCHP COOLING EXAMPLE, 65% REFRIGERANT CHARGE

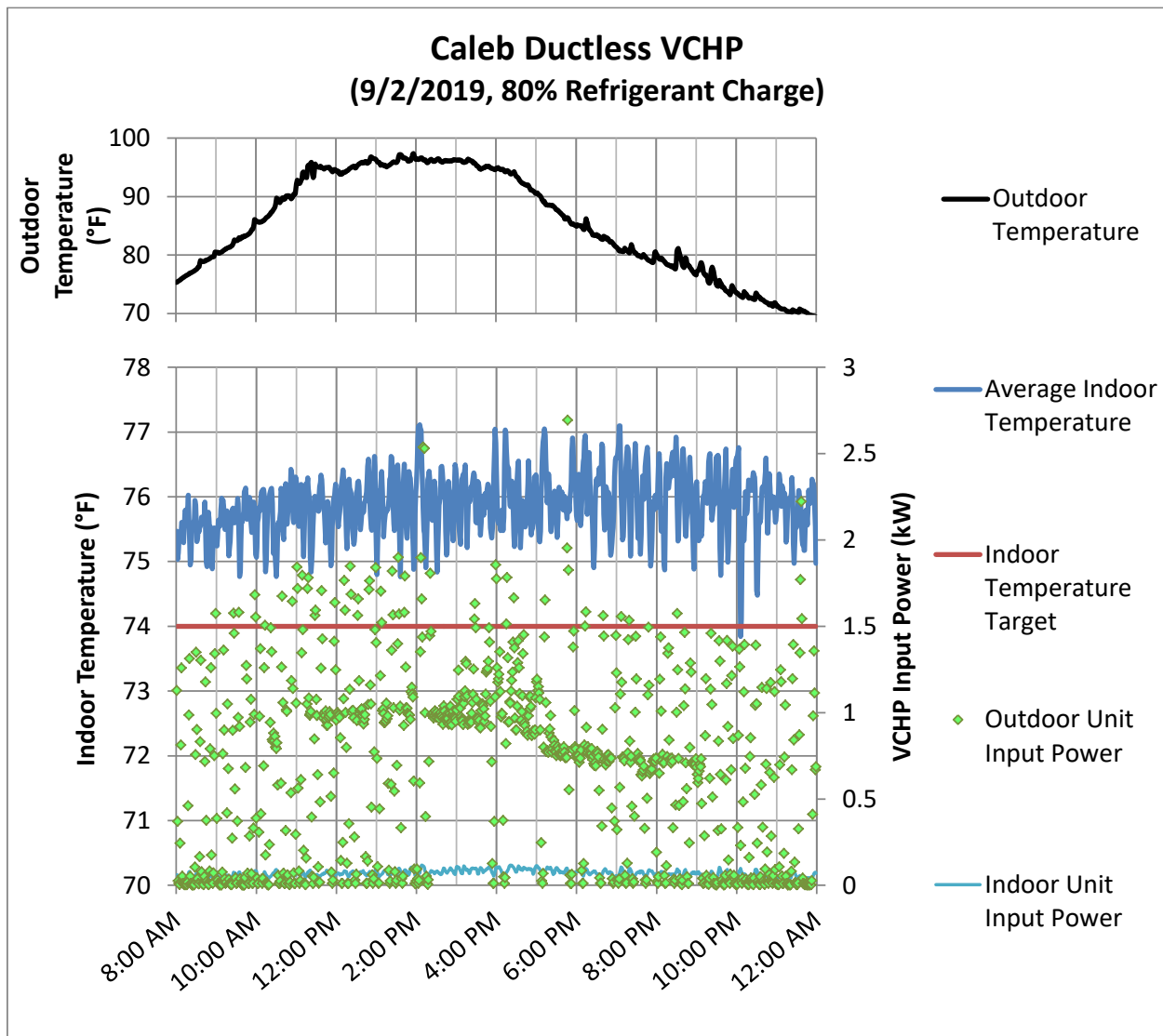


FIGURE 52. CALEB DUCTLESS VCHP COOLING EXAMPLE, 80% REFRIGERANT CHARGE

Figure 53 plots the Ductless VCHP input power against outdoor temperature at each of the four refrigerant levels. The plotted data includes all days the Ductless VCHP system operated during the 2019 cooling season, and each plotted point represents one minute. The large cluster of data points at about 1 kW reflects the system's preferred low speed.

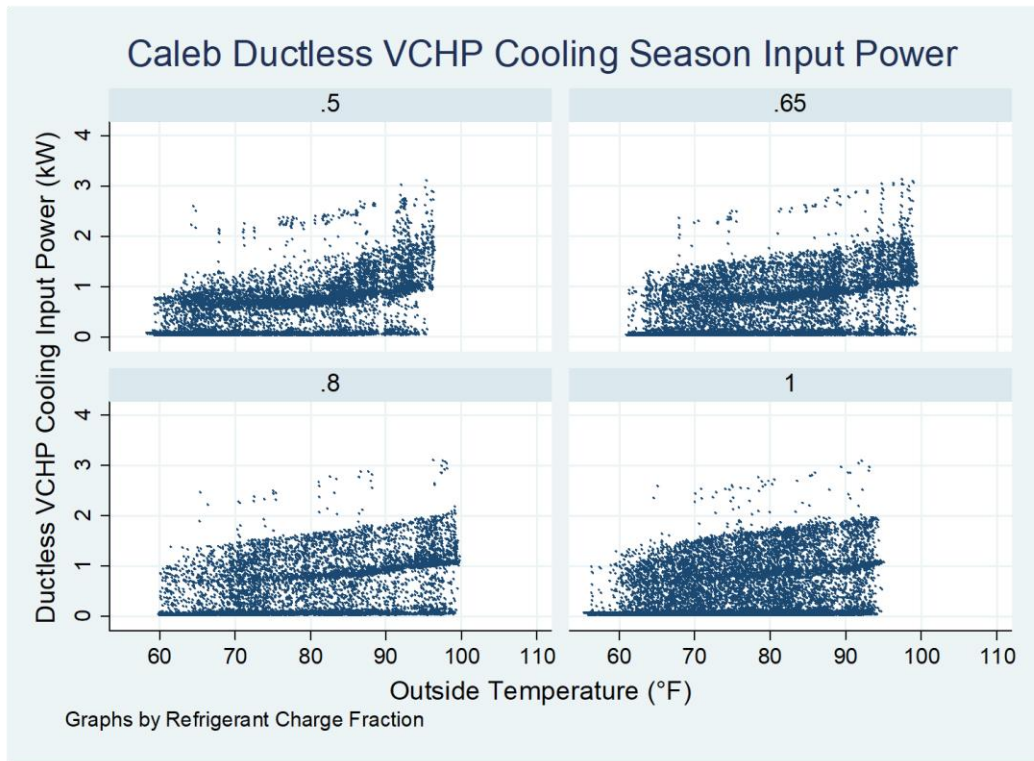


FIGURE 53. CALEB DUCTLESS VCHP INPUT POWER IN COOLING MODE

Cycling characteristics for the Ductless VCHP at each refrigerant level are tabulated against daily average outdoor temperature in Table 27. This system typically runs a large number of short cycles, exceeding 120 cycles per day on warm days. Low refrigerant charge increased the average cycle length and decreased the number of cycles per day.

TABLE 27. CALEB DUCTLESS VCHP CYCLING CHARACTERISTICS IN COOLING MODE

	DAILY AVERAGE OUTDOOR TEMPERATURE (°F)	REFRIGERANT LEVEL			
		50%	65%	80%	100%
Average Cycle Length (Minutes)	70	7.6	-	3.5	2.8
	75	8.6	4.8	4.1	3.4
	80	12.4	7.1	6.0	4.1
	85	-	8.4	6.9	-
Average Cycles Per Day	70	82.0	-	111.0	87.9
	75	58.3	108.6	128.0	113.5
	80	72.7	111.5	120.5	121.0
	85	-	100.0	103.5	-

DAILY ENERGY USE

The daily cooling energy use regression results for the Ductless VCHP are shown in Table 28. Figure 54 displays the monitored and regression predicted daily energy use for each refrigerant level. Figure 55 displays the monitored and regression predicted VCHP daily energy use plotted against daily average outdoor temperature, comparing the modeled results to directly monitored data.

TABLE 28. CALEB DUCTLESS VCHP DAILY COOLING ENERGY USE REGRESSION

SYSTEM	VARIABLE	COEFFICIENT	t	95% CONFIDENCE INTERVAL	
Ductless VCHP	E _{Ref}	0.6140	18.67	0.5473	0.6807
	E _{Ref_R50}	0.4766	17.34	0.4208	0.5323
	E _{Ref_R65}	0.1721	7.02	0.1224	0.2218
	E _{Ref_R80}	0.0492	1.93	-0.0025	0.1009
	Constant	0.3693	1.31	-0.2035	0.9421
	R ²	0.98			
	Daily Standby kWh	1.42			

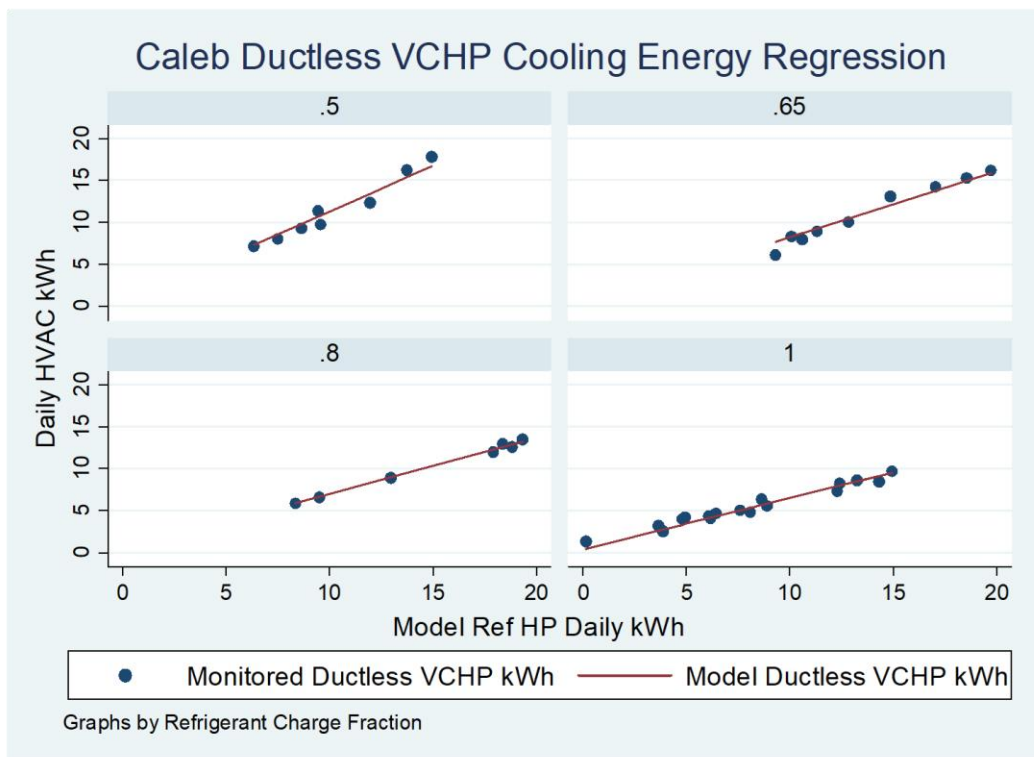


FIGURE 54. CALEB DUCTLESS VCHP DAILY COOLING ENERGY REGRESSION

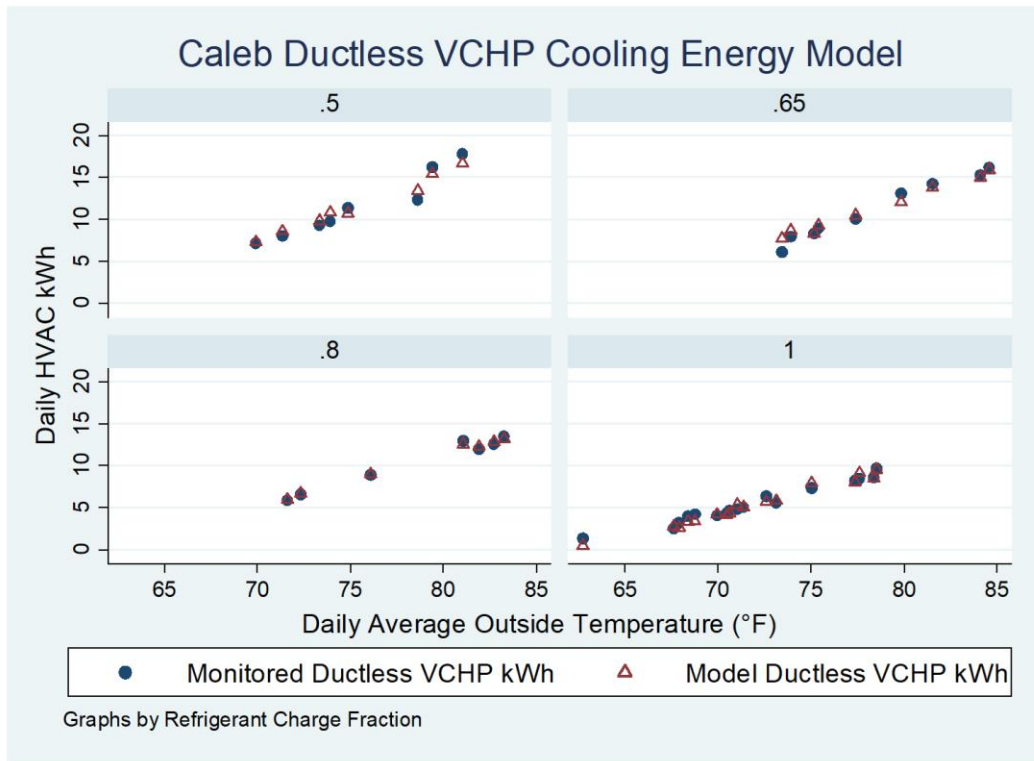


FIGURE 55. CALEB DUCTLESS VCHP MONITORED AND MODEL PREDICTED DAILY COOLING ENERGY

The regression predicted normalized seasonal energy use estimates are shown in Table 29. The daily energy use analysis shows efficiency reductions at all three refrigerant undercharge levels, with a loss of 37% at 50% refrigerant charge.

TABLE 29. CALEB DUCTLESS VCHP NORMALIZED COOLING SEASON ENERGY USE

SYSTEM	REFRIGERANT LEVEL	SEASONAL ENERGY USE (kWh)	SEASONAL ENERGY USE RELATIVE TO CORRECT REFRIGERANT CHARGE	IMPLIED EFFICIENCY RELATIVE TO CORRECT REFRIGERANT CHARGE
Ductless VCHP	50%	1787.1	159%	63%
	65%	1365.2	121%	83%
	80%	1195.0	106%	94%
	100%	1126.8	100%	100%

AFTERNOON AND EVENING DEMAND

Refrigerant undercharge had a large effect on afternoon and evening demand of the Ductless VCHP. Demand increased at all refrigerant undercharge levels, and increased with the amount of refrigerant undercharge. Demand during hot afternoon hours increased by as much as 90% at 50% refrigerant charge. The average hourly

demand relative to performance at correct refrigerant charge is tabulated in Table 30. The monitored energy use during each hour for each refrigerant level is plotted in Figure 56.

TABLE 30. CALEB DUCTLESS VCHP AVERAGE HOURLY DEMAND RELATIVE TO PERFORMANCE AT CORRECT REFRIGERANT CHARGE

REFRIGERANT LEVEL	HOUR	HOURLY AVERAGE OUTDOOR TEMPERATURE (°F)				
		80	85	90	95	100
50%	2-3 PM	-	144%	145%	183%	-
	3-4 PM	141%	170%	139%	176%	-
	4-5 PM	172%	165%	154%	182%	-
	5-6 PM	145%	137%	159%	193%	-
	6-7 PM	149%	160%	159%	-	-
	7-8 PM	126%	144%	-	-	-
	8-9 PM	138%	-	-	-	-
	9-10 PM	121%	-	-	-	-
65%	2-3 PM	-	120%	135%	132%	-
	3-4 PM	-	140%	114%	123%	-
	4-5 PM	-	127%	100%	132%	-
	5-6 PM	149%	106%	125%	151%	-
	6-7 PM	124%	135%	122%	-	-
	7-8 PM	133%	127%	-	-	-
	8-9 PM	115%	-	-	-	-
	9-10 PM	125%	-	-	-	-
80%	2-3 PM	-	115%	124%	135%	-
	3-4 PM	-	120%	100%	145%	-
	4-5 PM	-	126%	-	114%	-
	5-6 PM	134%	113%	119%	116%	-
	6-7 PM	112%	113%	101%	-	-
	7-8 PM	131%	115%	-	-	-
	8-9 PM	113%	-	-	-	-
	9-10 PM	116%	-	-	-	-

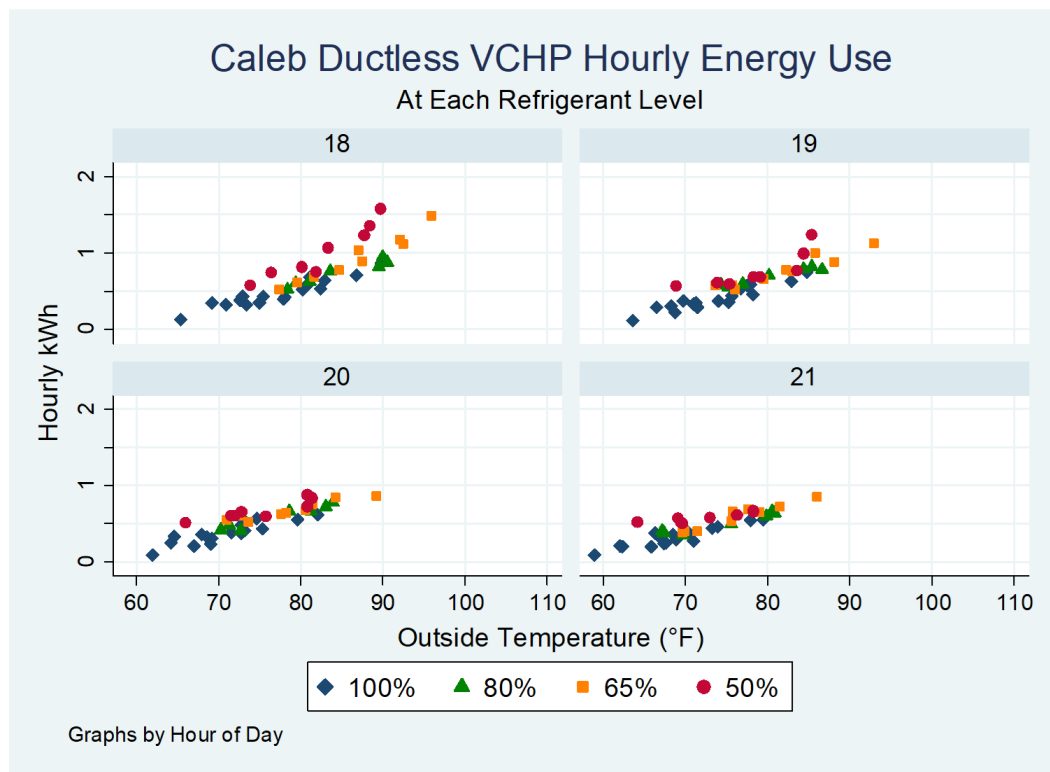
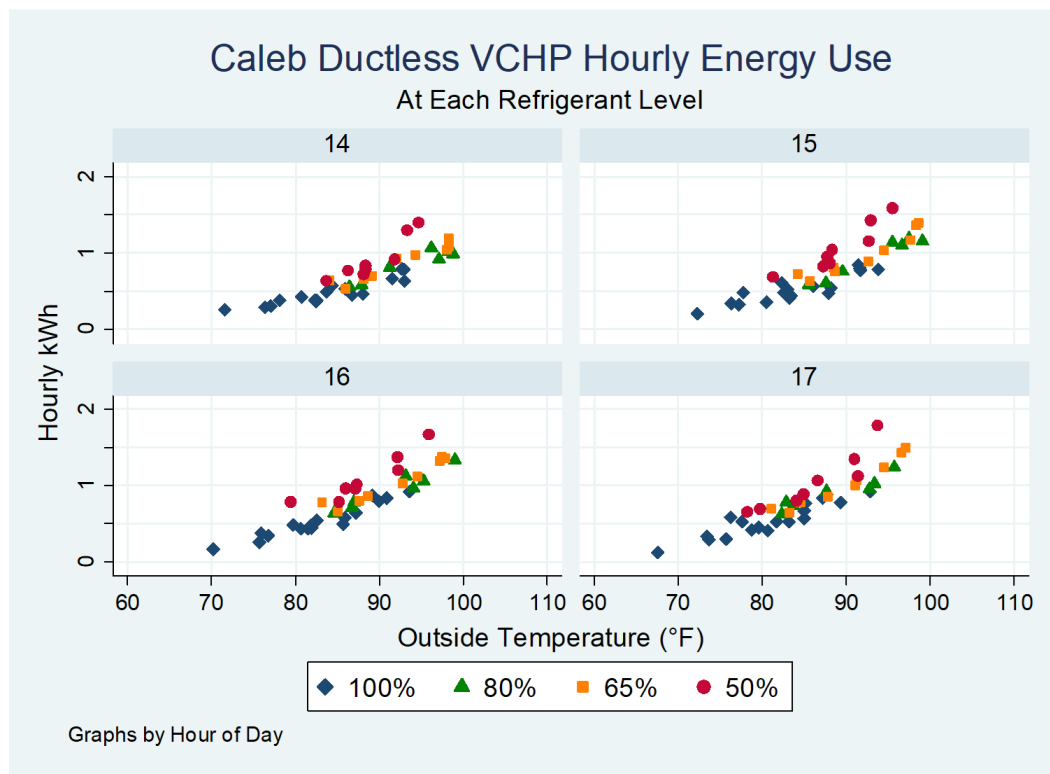


FIGURE 56. CALEB DUCTLESS VCHP COOLING SEASON HOURLY ENERGY USE AT EACH REFRIGERANT LEVEL

HEATING SEASON

Average temperatures of each room relative to the target temperature are shown in Figure 57. Average indoor temperatures relative to the temperatures at correct refrigerant charge are shown in Figure 58. The plotted values represent the average of all minutes that occurred during hours with compressor operation during the hour, indicating that the system was providing heating to the house during the hour. This system is controlled by thermostats located in each room.

The Ductless VCHP system overheats some rooms of the house. The system is not capable of delivering refrigerant to a single indoor unit in heating mode, so when the compressor operates multiple rooms receive heat even if the thermostat in only one room was calling for heat. Overheating was observed at all refrigerant levels but was slightly reduced at 50% refrigerant charge.

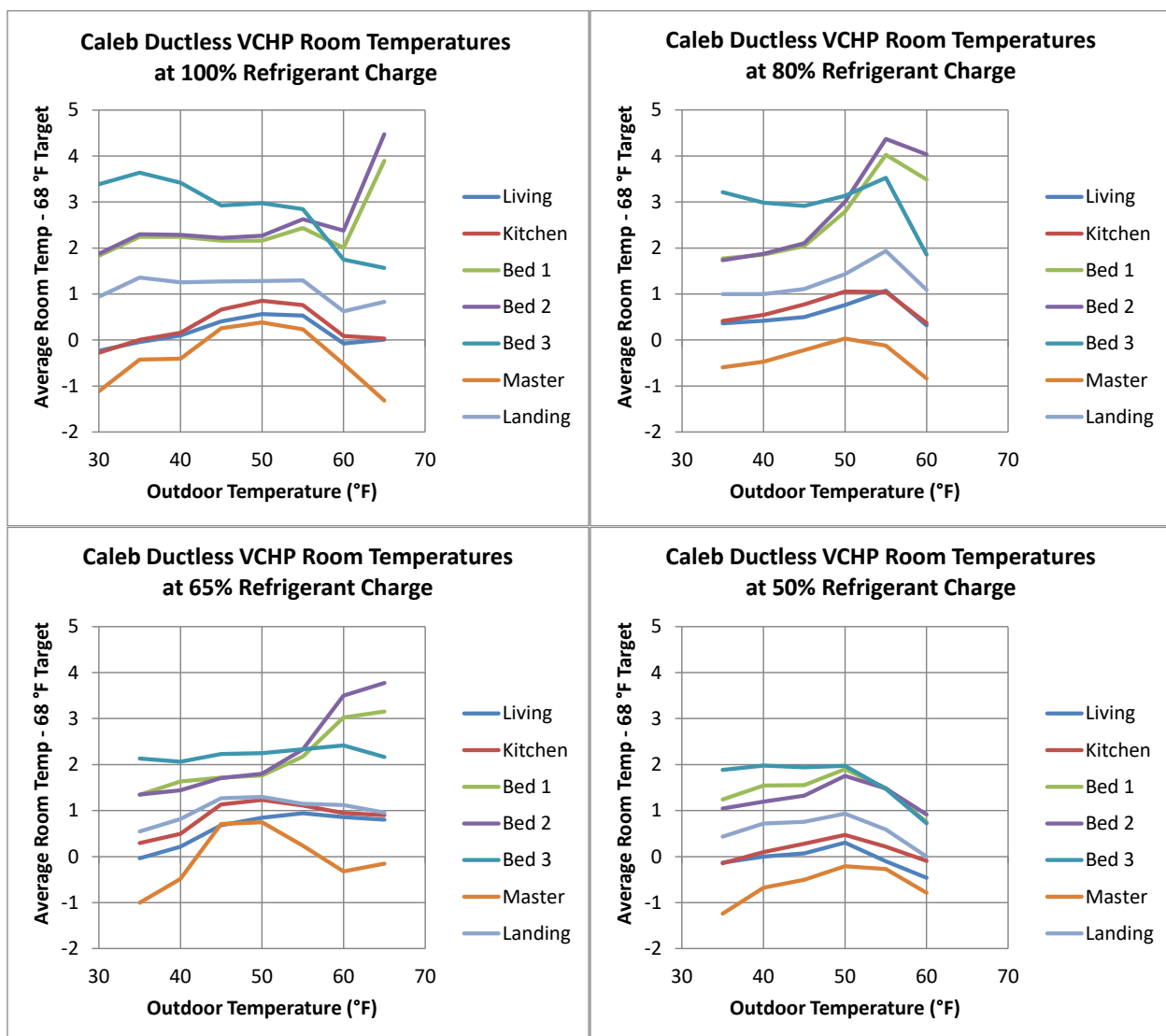


FIGURE 57. CALEB DUCTLESS VCHP HEATING SEASON INDOOR TEMPERATURE DELTA TO TARGET

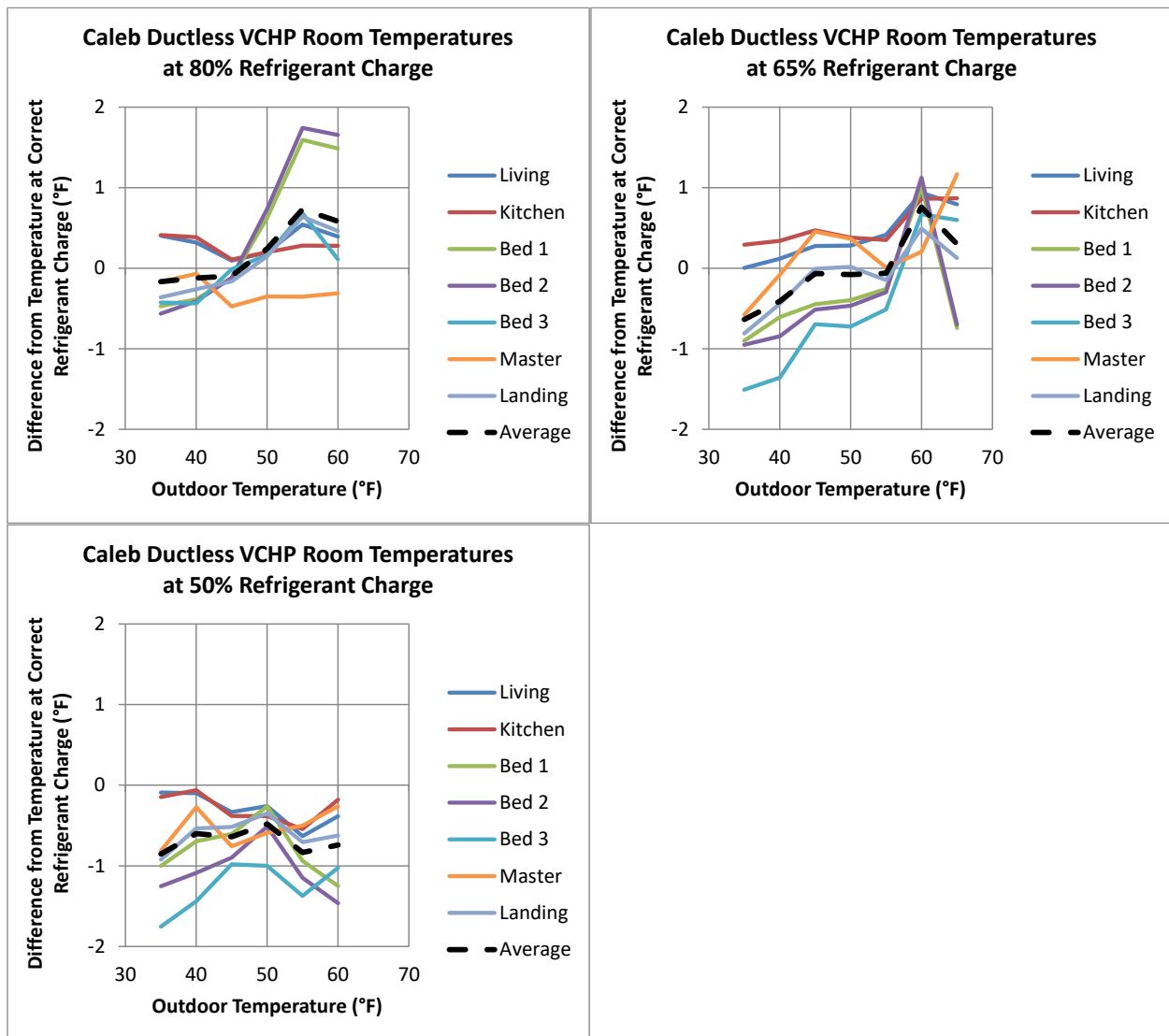


FIGURE 58. CALEB DUCTLESS VCHP HEATING SEASON INDOOR TEMPERATURES AT REFRIGERANT UNDERCHARGE CONDITIONS RELATIVE TO TEMPERATURES AT CORRECT REFRIGERANT CHARGE

Figure 59 and Figure 60 show examples of how this system operated on days with similar outdoor temperature at correct refrigerant charge and at 50% refrigerant charge. Each plotted point represents one minute. The system cycled on both days.

The sudden negative changes in indoor temperature at 1:30PM on the day with correct refrigerant charge and at 5AM on the day with 50% refrigerant charge are defrost cycles. Defrost was infrequent, with only 14 cycles observed during heating season. Nine of the 14 defrost cycles occurred at 50% refrigerant charge.

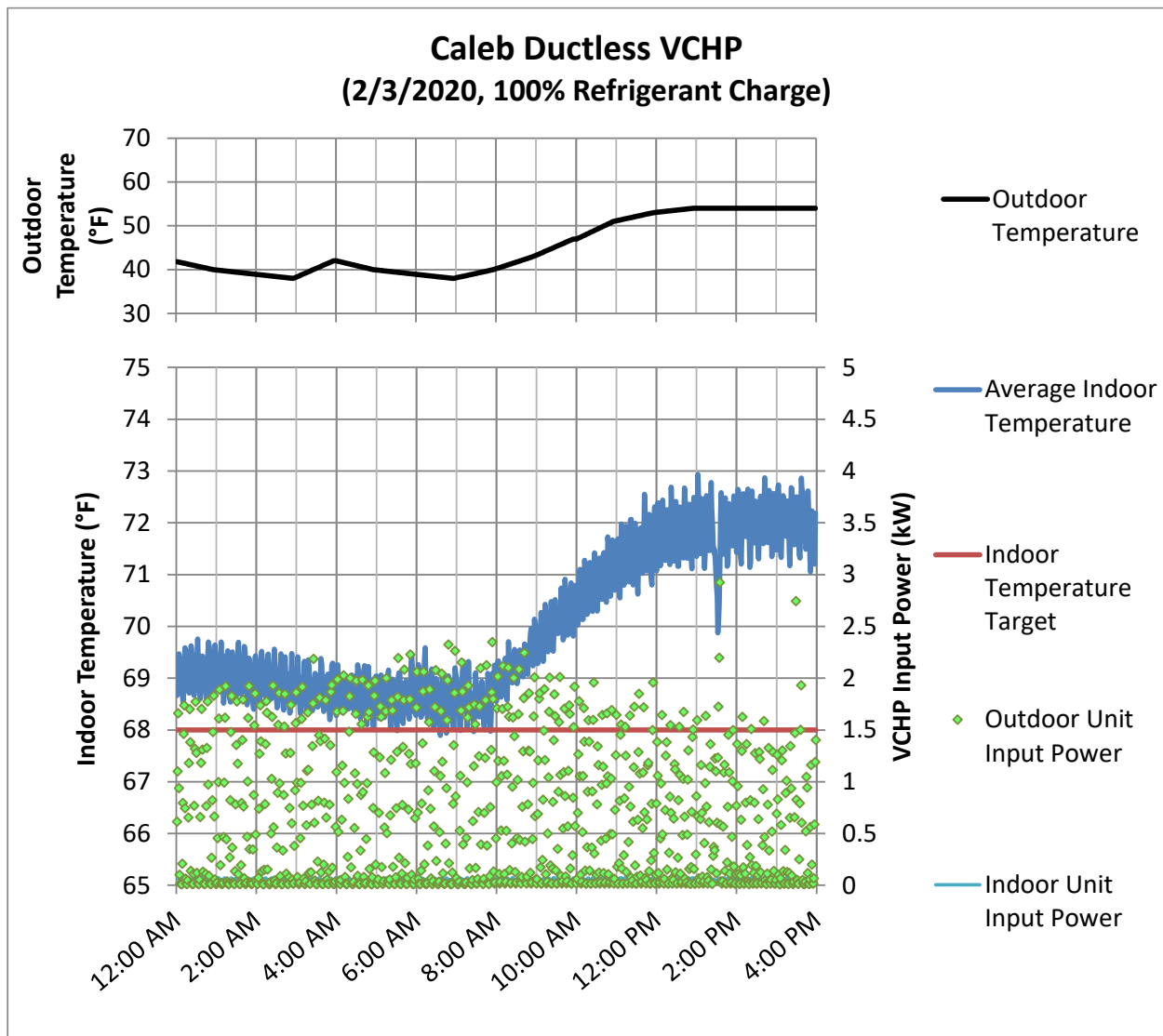


FIGURE 59. CALEB DUCTLESS VCHP HEATING EXAMPLE, CORRECT REFRIGERANT CHARGE

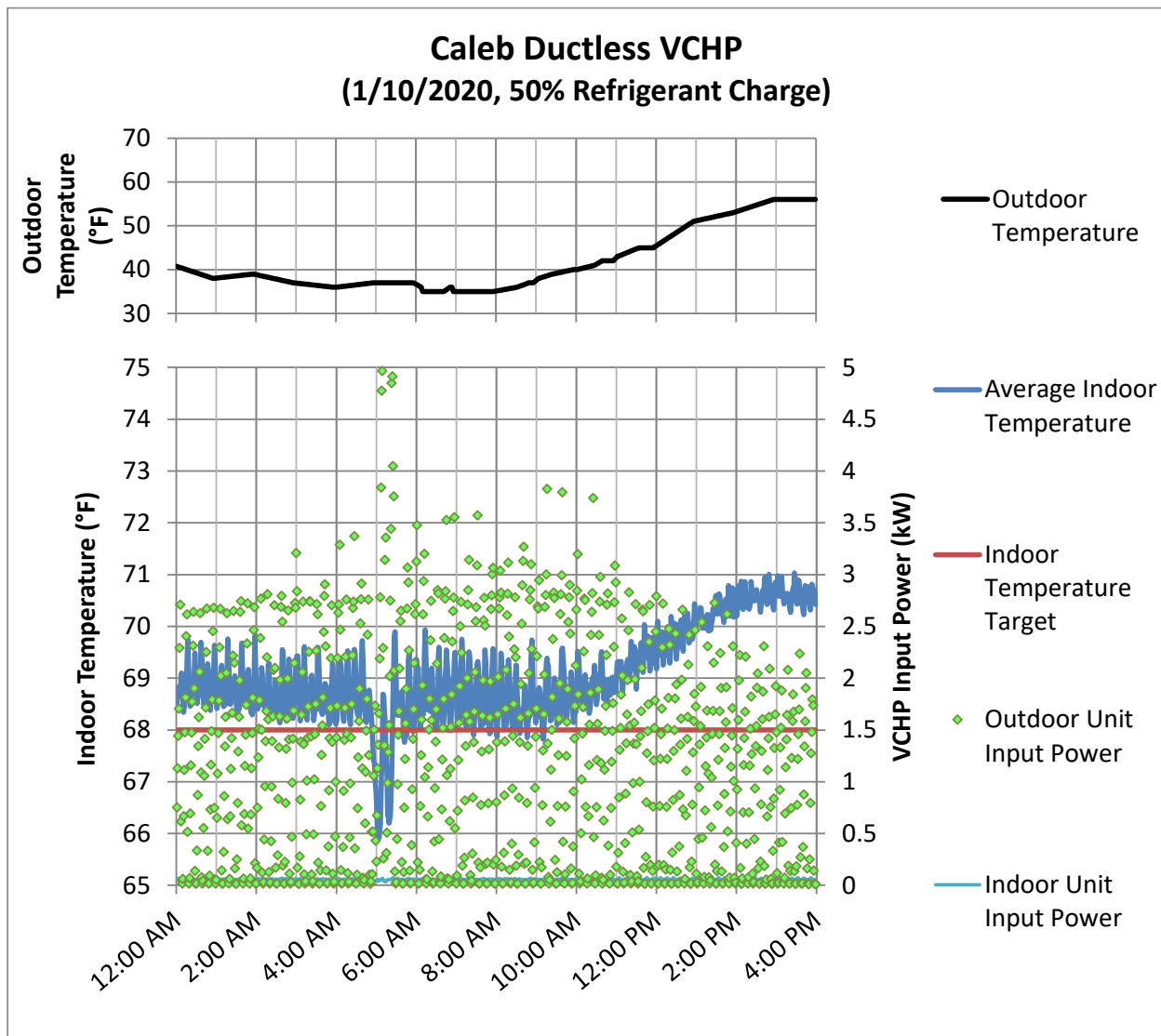


FIGURE 60. CALEB DUCTLESS VCHP HEATING EXAMPLE, 50% REFRIGERANT CHARGE

Figure 61 and Figure 62 show days at 65% and 80% refrigerant charge. The 65% day is warmer due to mild weather throughout the entire 65% testing period.

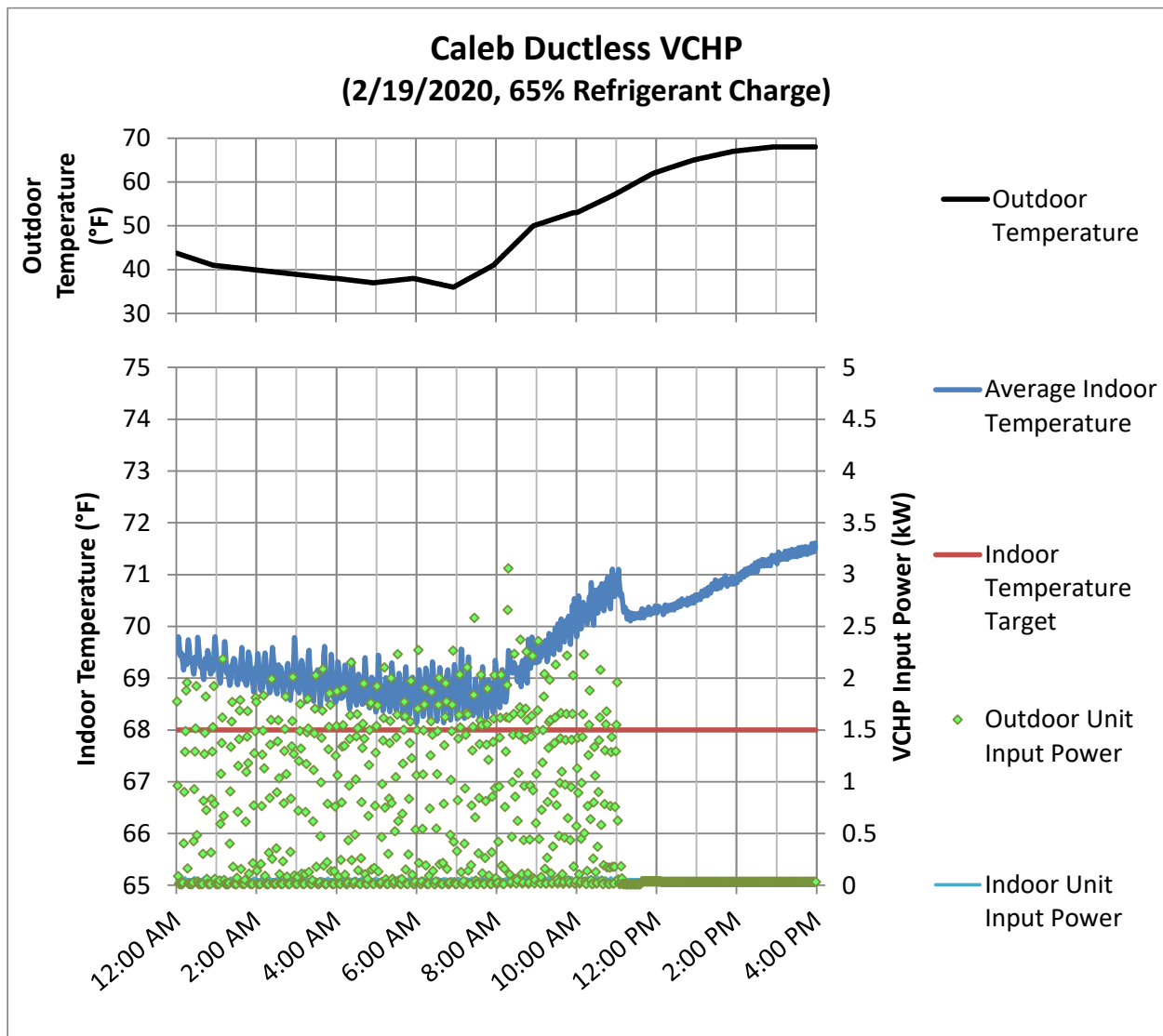


FIGURE 61. CALEB DUCTLESS VCHP HEATING EXAMPLE, 65% REFRIGERANT CHARGE

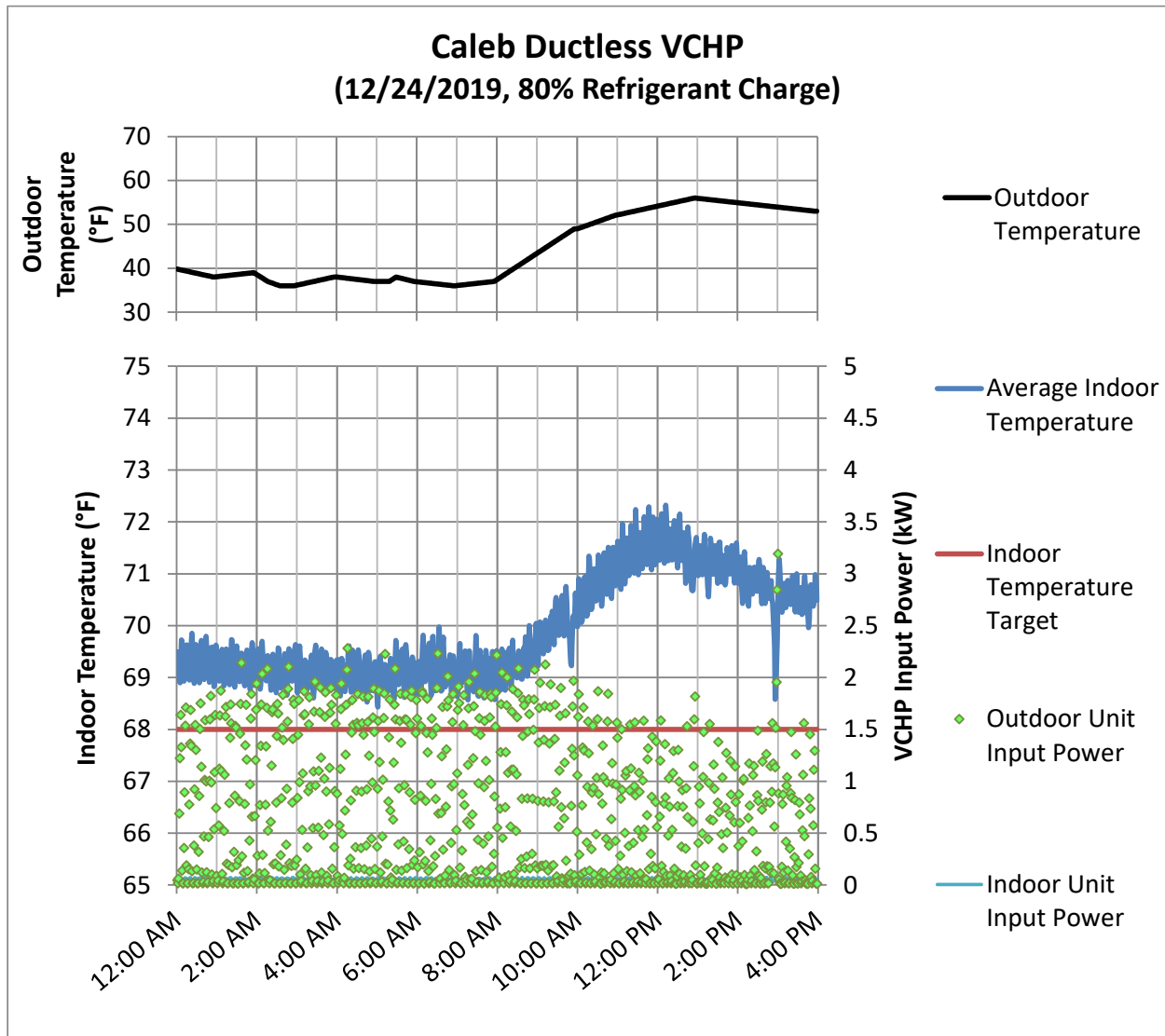


FIGURE 62. CALEB DUCTLESS VCHP HEATING EXAMPLE, 80% REFRIGERANT CHARGE

Figure 63 plots the Ductless VCHP input power against outdoor temperature at each of the four refrigerant levels. The plotted data includes all days the Ductless VCHP system operated during the 2019-2020 heating season, and each plotted point represents one minute.

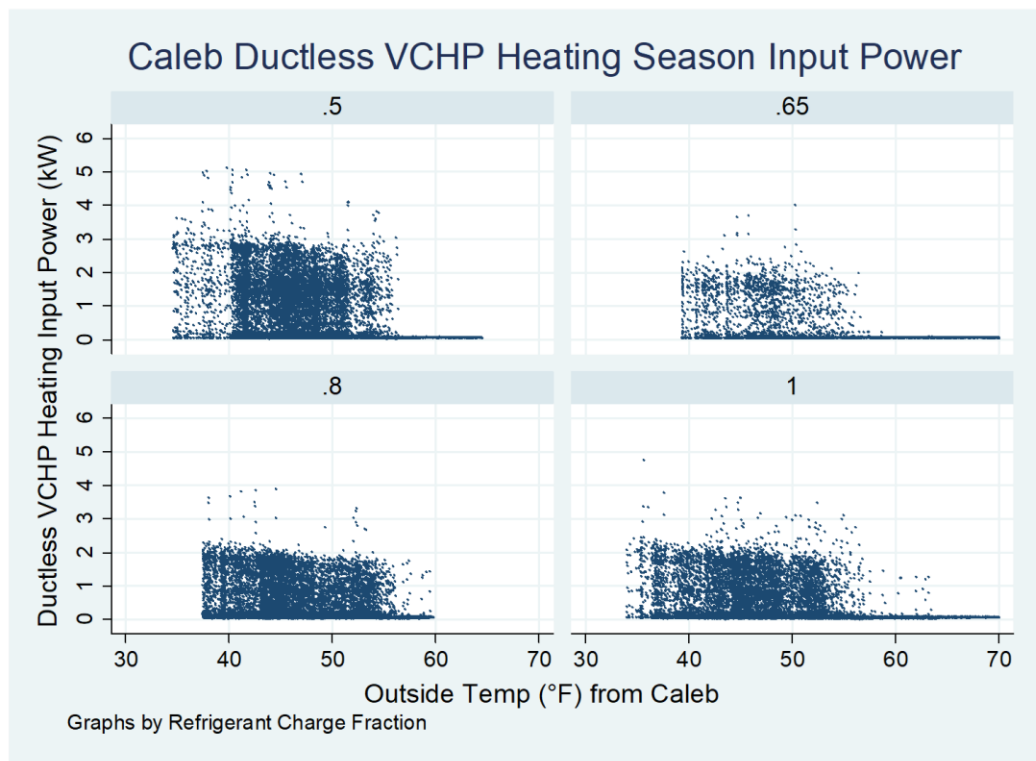


FIGURE 63. CALEB DUCTLESS VCHP INPUT POWER IN HEATING MODE

Cycling characteristics for the Ductless VCHP at each refrigerant level are tabulated against daily average outdoor temperature in Table 31. This system typically runs a large number of short cycles, often exceeding 100 cycles per day. There is no clear relationship between refrigerant levels and cycling behavior.

TABLE 31. CALEB DUCTLESS VCHP CYCLING CHARACTERISTICS IN HEATING MODE

	DAILY AVERAGE OUTDOOR TEMPERATURE (°F)	REFRIGERANT LEVEL			
		50%	65%	80%	100%
Average Cycle Length (Minutes)	45	6.6	-	3.6	3.8
	50	6.2	5.2	3.9	3.8
	55	6.4	4.9	-	3.5
	60	-	4.4	-	3.6
Average Cycles Per Day	45	144.4	-	183.5	178.3
	50	147.0	62.0	147.0	87.4
	55	47.0	32.5	-	64.4
	60	-	13.3	-	15.0

DAILY ENERGY USE

The daily heating energy use regression results for the Ductless VCHP are shown in Table 32. Figure 64 displays the monitored and regression predicted daily energy use for each refrigerant level. Figure 65 displays the monitored and regression predicted VCHP daily energy use plotted against daily average outdoor temperature, comparing the modeled results to directly monitored data.

TABLE 32. CALEB DUCTLESS VCHP DAILY HEATING ENERGY REGRESSION

SYSTEM	VARIABLE	COEFFICIENT	t	95% CONFIDENCE INTERVAL	
Ductless VCHP	E _{Ref}	0.3138	14.60	0.2701	0.3574
	E _{Ref_R50}	0.2949	15.96	0.2573	0.3324
	E _{Ref_R65}	0.1032	1.87	-0.0087	0.2152
	E _{Ref_R80}	0.0287	1.57	-0.0085	0.0660
	Constant	0.4504	1.02	-0.4484	1.3493
	R ²	0.97			
	Daily Standby kWh	1.9			

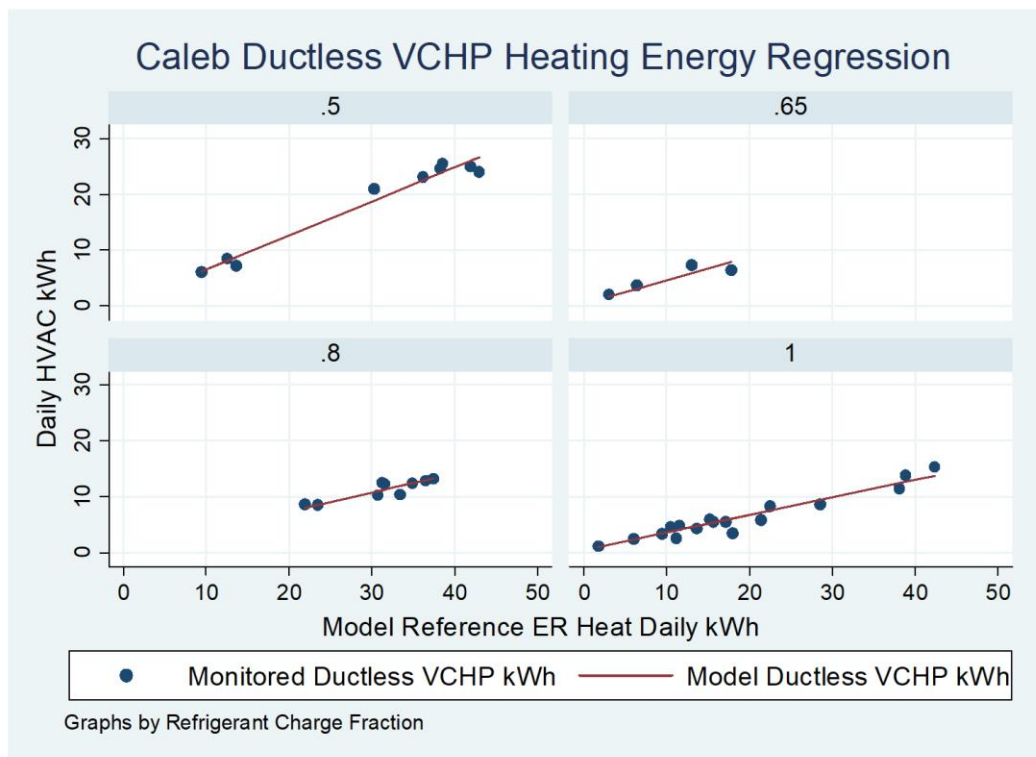


FIGURE 64. CALEB DUCTLESS VCHP DAILY HEATING ENERGY REGRESSION

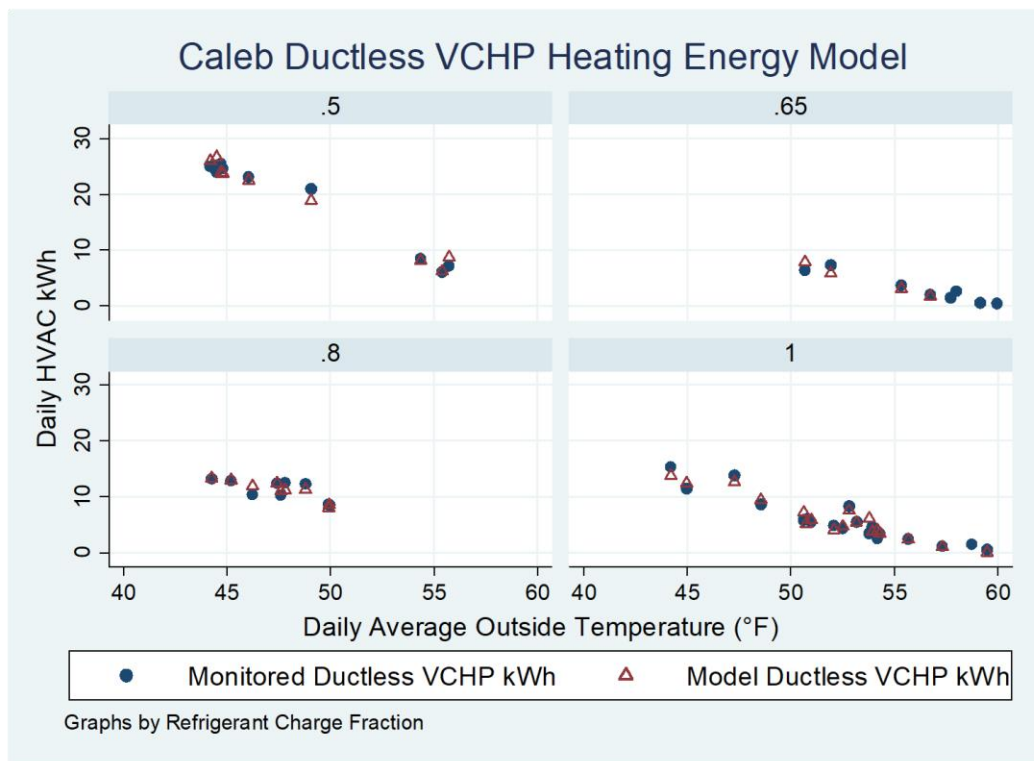


FIGURE 65. CALEB DUCTLESS VCHP MONITORED AND MODEL PREDICTED DAILY HEATING ENERGY

The regression predicted normalized seasonal energy use estimates are shown in Table 33. The daily energy use analysis shows an efficiency reduction at all refrigerant levels, with a 42% reduction at 50% refrigerant charge.

TABLE 33. CALEB DUCTLESS VCHP NORMALIZED HEATING SEASON ENERGY USE

SYSTEM	REFRIGERANT LEVEL	SEASONAL ENERGY USE (kWh)	SEASONAL ENERGY USE RELATIVE TO CORRECT REFRIGERANT CHARGE	IMPLIED EFFICIENCY RELATIVE TO CORRECT REFRIGERANT CHARGE
Ductless VCHP	50%	3021.9	173%	58%
	65%	2192.4	126%	80%
	80%	1869.9	107%	93%
	100%	1745.5	100%	100%

GRANGE HOUSE, REFERENCE SYSTEM

Average temperatures of each room relative to the target temperature are shown in Figure 66 for times when the reference HP system was operating during cooling season, and for times when the electric resistance heaters were operating during heating season. The plotted values represent the average of all minutes that occurred during hours with compressor or resistance heater operation during the hour, indicating that the system was providing cooling or heating to the house during the hour. The reference heat pump system is controlled by a single thermostat located in the kitchen. The electric resistance heaters in each room are individually controlled by the DAS system based on the monitored temperature in the room. The reference systems maintained average temperatures within 1 °F of target.

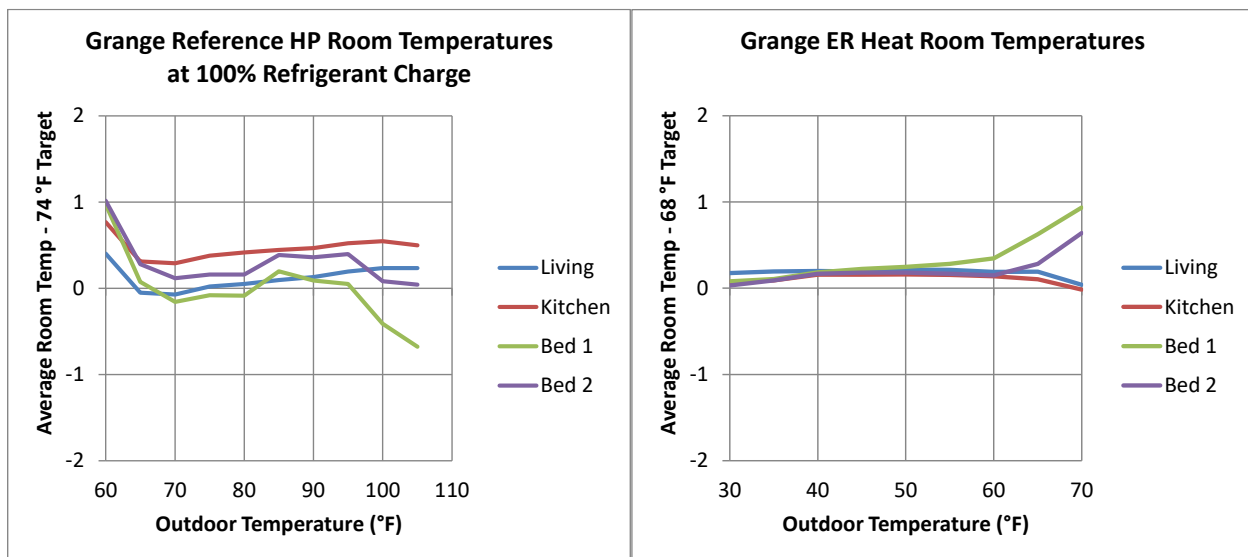


FIGURE 66. GRANGE REFERENCE SYSTEM INDOOR TEMPERATURE DELTA TO TARGET

DAILY ENERGY USE

The daily energy use regression results for the reference HP and electric resistance heat are shown in Table 34. Figure 67 displays monitored daily energy use and the regression model for cooling season, and Figure 68 displays the monitored data and the regression model for heating season.

TABLE 34. GRANGE REFERENCE SYSTEM DAILY ENERGY USE REGRESSIONS

SEASON	T _{AVG}	T _{HIGH}	T _{LOW}	t _{DAY}	CONST	R ²	DAILY STANDBY KWH
Cooling	0.2389	0.1016	0.1771	0.8094	-34.20	0.95	0.26
Heating	-0.4474	-0.4200	-0.4522	-3.7472	84.25	0.96	0

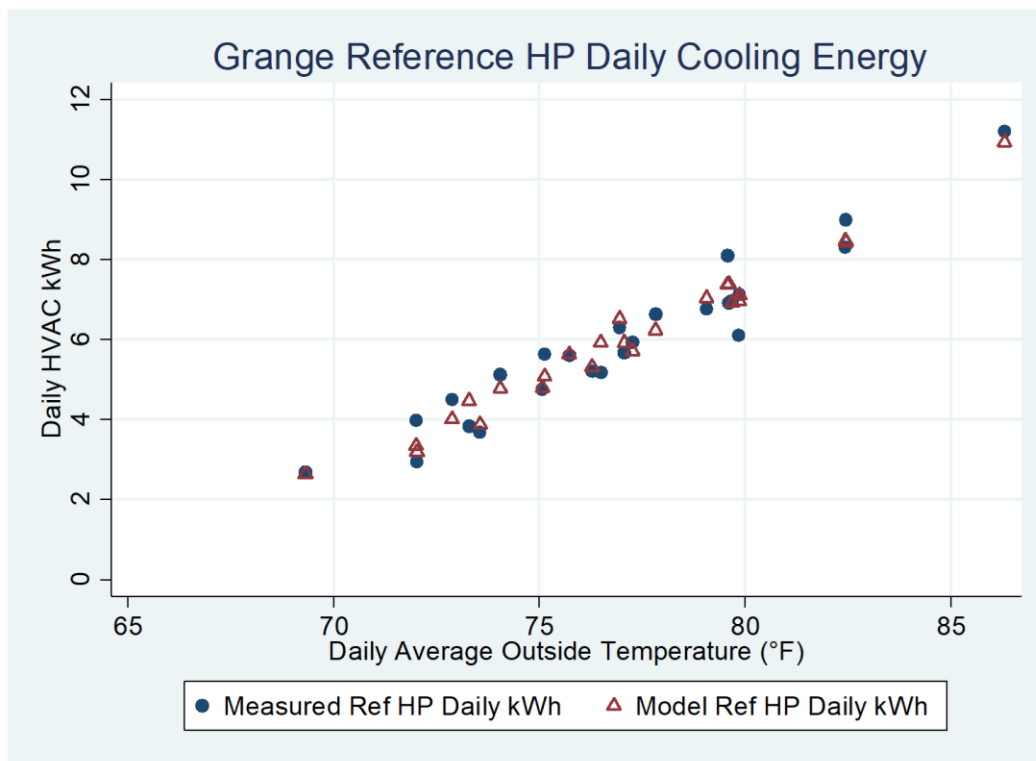


FIGURE 67. GRANGE REFERENCE HP DAILY COOLING ENERGY REGRESSION MODEL

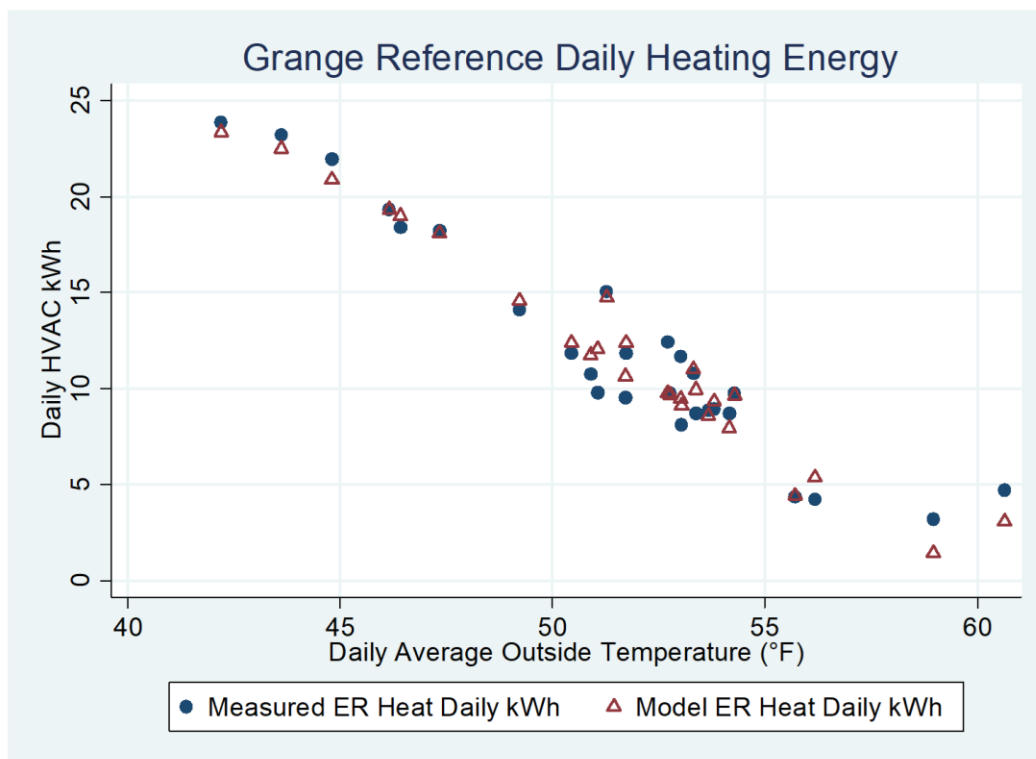


FIGURE 68. GRANGE ELECTRIC RESISTANCE HEAT DAILY ENERGY REGRESSION MODEL

GRANGE HOUSE, 0.75 TON VCHP

COOLING SEASON

The 0.75 ton VCHP system maintained similar indoor temperatures at all refrigerant levels. There was a small increase of about 0.8 °F in average indoor temperature on hot afternoons at 50% undercharge.

Average temperatures of each room relative to the target temperature are shown in Figure 69. Average indoor temperatures relative to the temperatures at correct refrigerant charge are shown in Figure 70. The plotted values represent the average of all minutes that occurred during hours with compressor operation during the hour, indicating that the system was providing cooling to the house during the hour. This system is controlled by a single thermostat located in the kitchen.

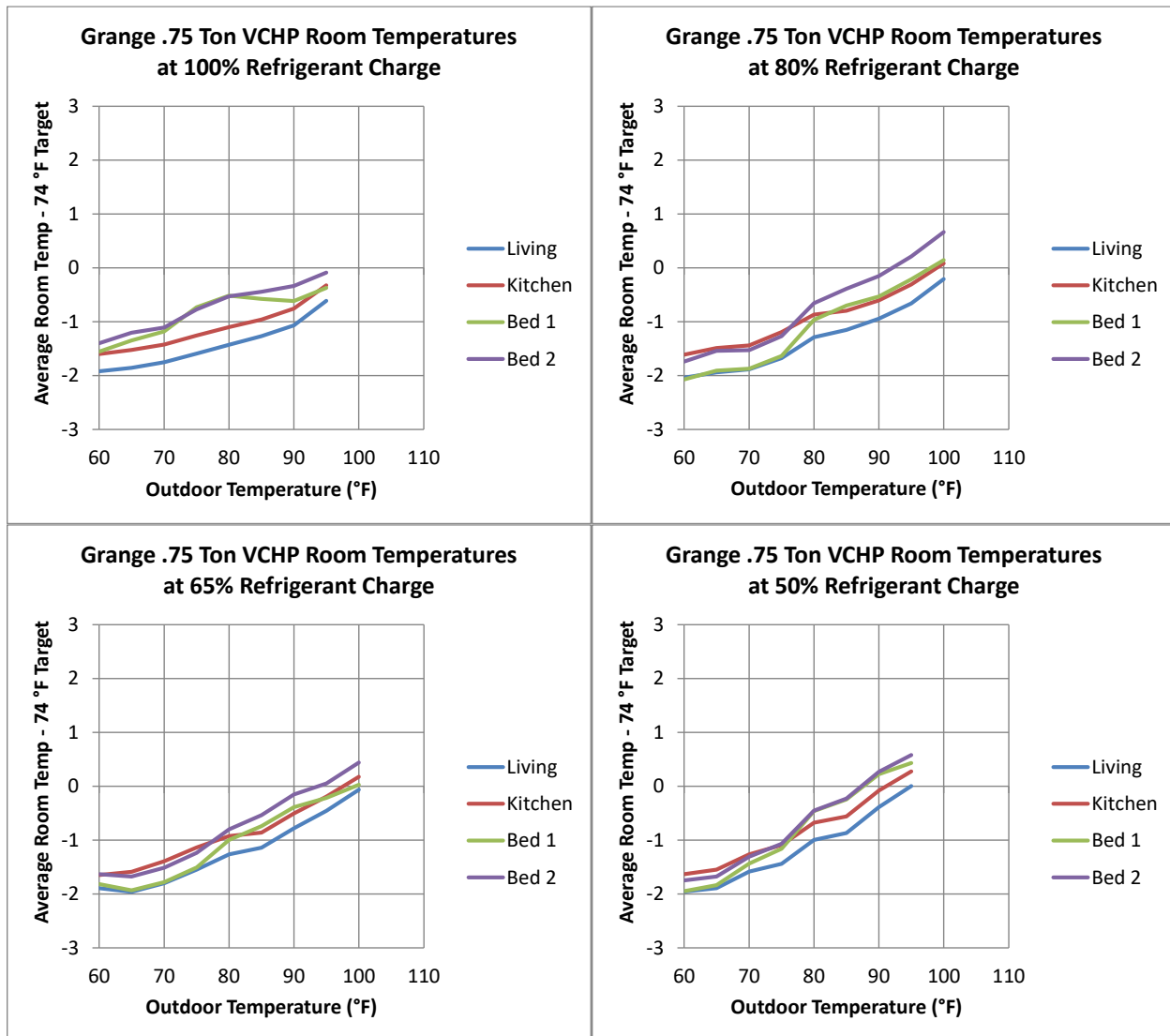


FIGURE 69. GRANGE .75 TON VCHP COOLING SEASON INDOOR TEMPERATURE DELTA TO TARGET

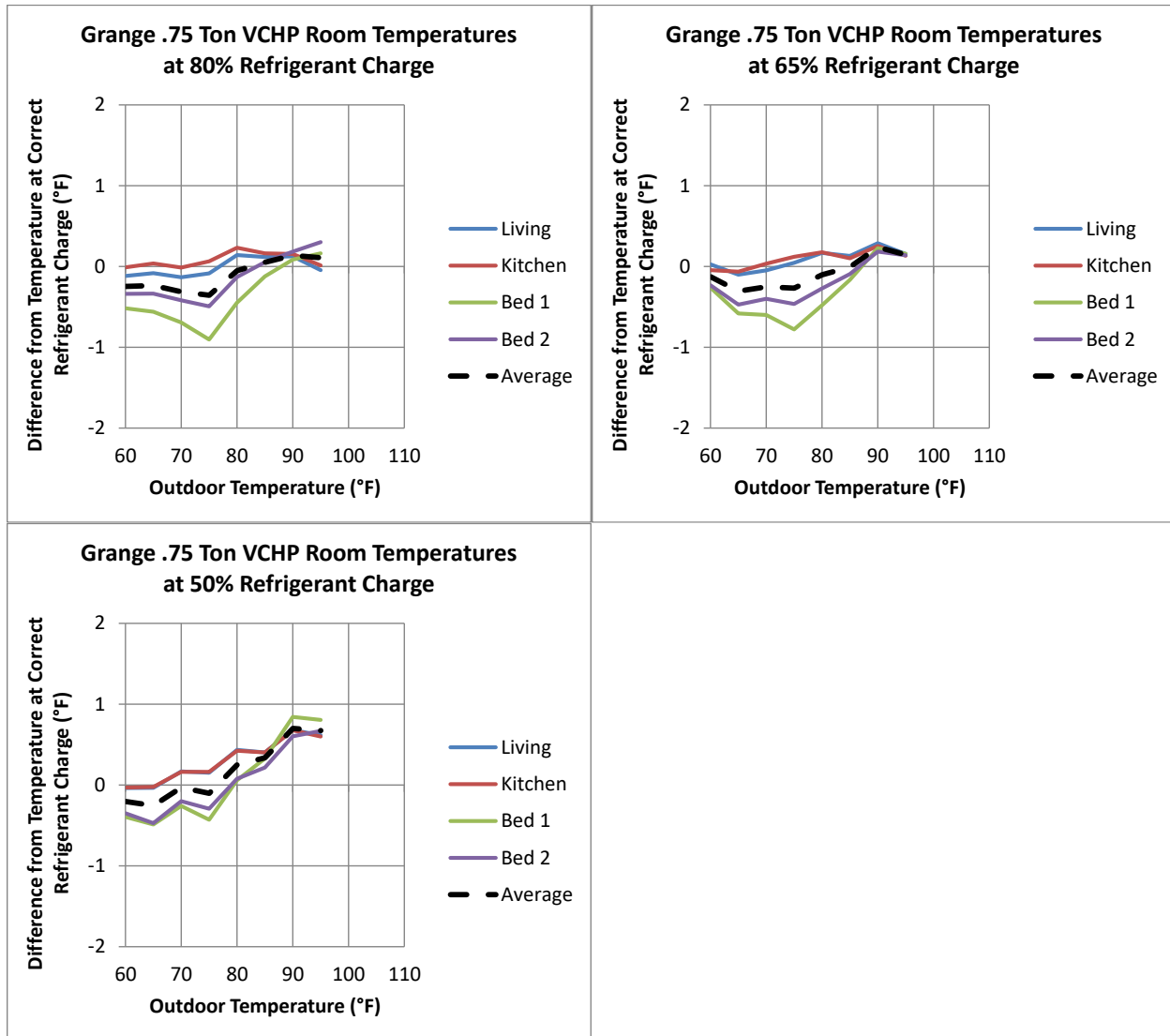


FIGURE 70. GRANGE 0.75 TON VCHP COOLING SEASON INDOOR TEMPERATURES AT REFRIGERANT UNDERCHARGE CONDITIONS RELATIVE TO TEMPERATURES AT CORRECT REFRIGERANT CHARGE

Figure 71 and Figure 72 show examples of how this system operated on days with similar outdoor temperature at correct refrigerant charge and at 50% refrigerant charge. Each plotted point represents one minute.

In the morning of both days, when outdoor temperatures were mild and cooling loads were low, the system cycled and maintained indoor temperatures about 1.5 °F below target. The scattering of higher outdoor unit input power data points during the morning hours reflects that this system began each cycle with capacity increasing to higher than the minimum level before returning to a lower speed. As outdoor temperature warmed and cooling loads increased, the system settled into constant low speed operation. When indoor temperatures began to exceed target, outdoor unit power increased indicating that the unit increased compressor speed to

deliver more cooling capacity. In the late evening of both days, the system returned to low speed.

Figure 71 and Figure 72 show that while indoor temperatures were maintained near target in both cases, low refrigerant charge resulted in compressor speed increasing earlier in the day, increasing to a higher level, and higher speed operation continuing for a longer period of time than at correct refrigerant charge.

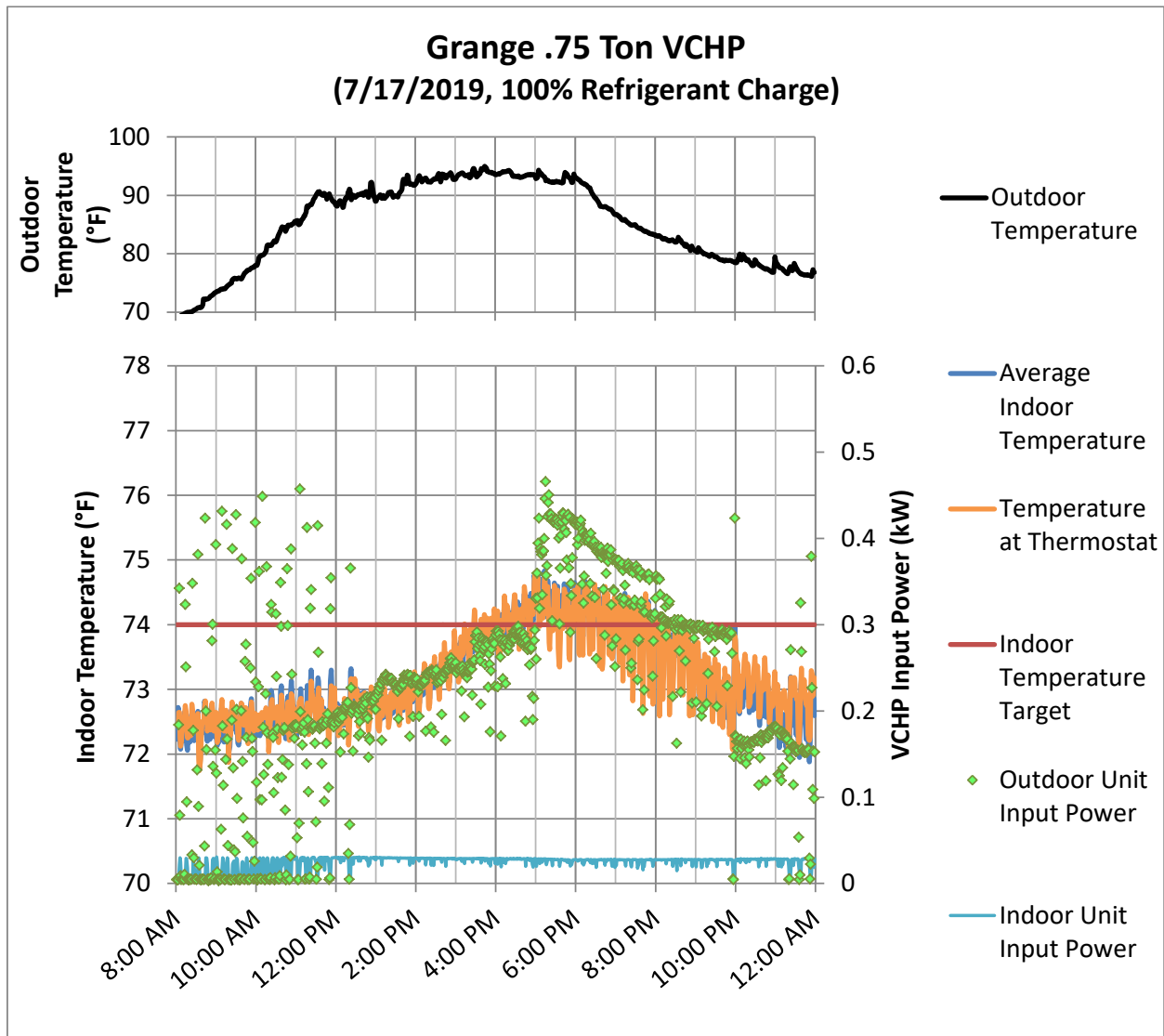


FIGURE 71. GRANGE 0.75 TON VCHP COOLING EXAMPLE, CORRECT REFRIGERANT CHARGE

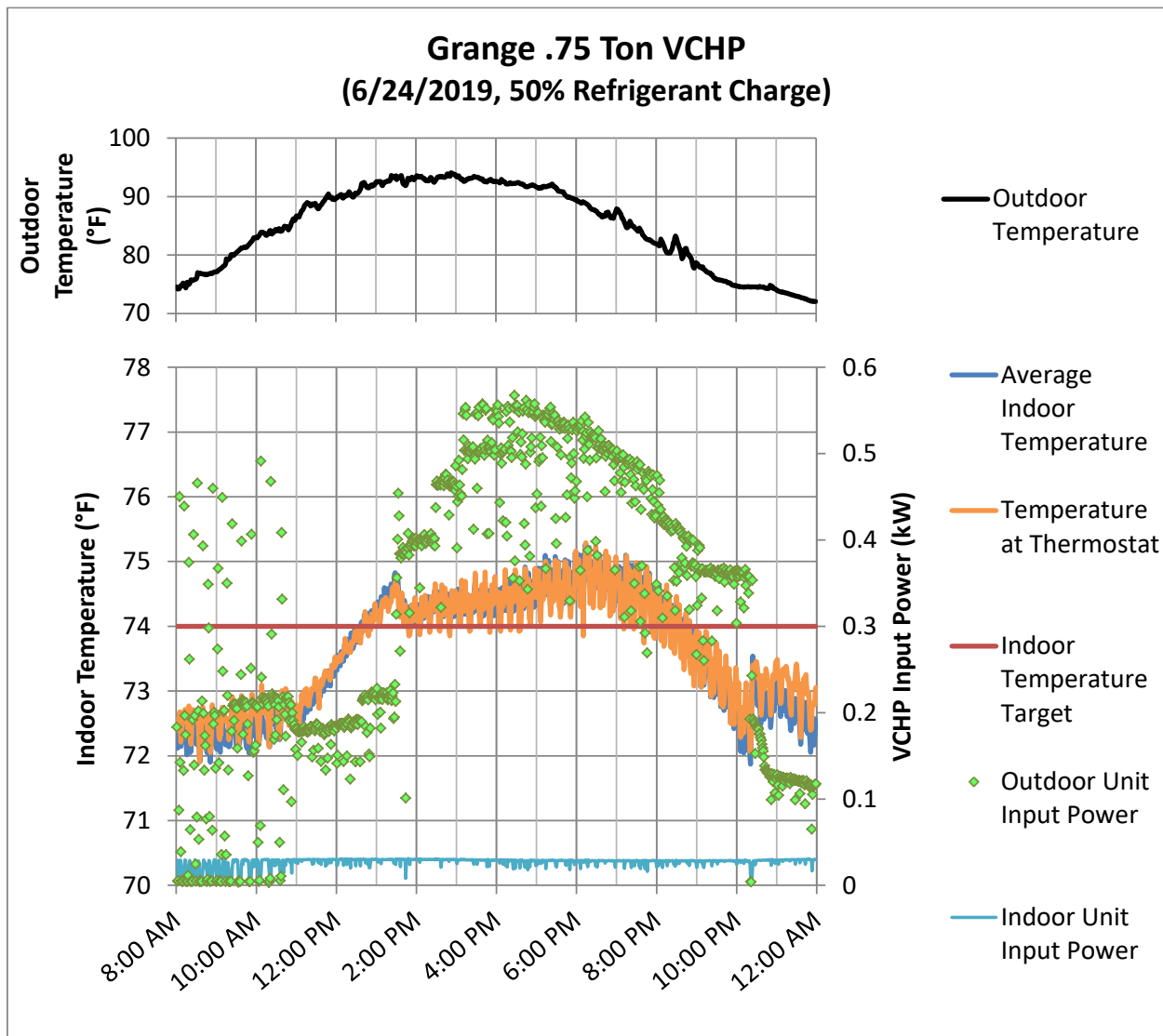


FIGURE 72. GRANGE 0.75 TON VCHP COOLING EXAMPLE, 50% REFRIGERANT CHARGE

Figure 73 and Figure 74 show similar days at 65% and 80% refrigerant charge.

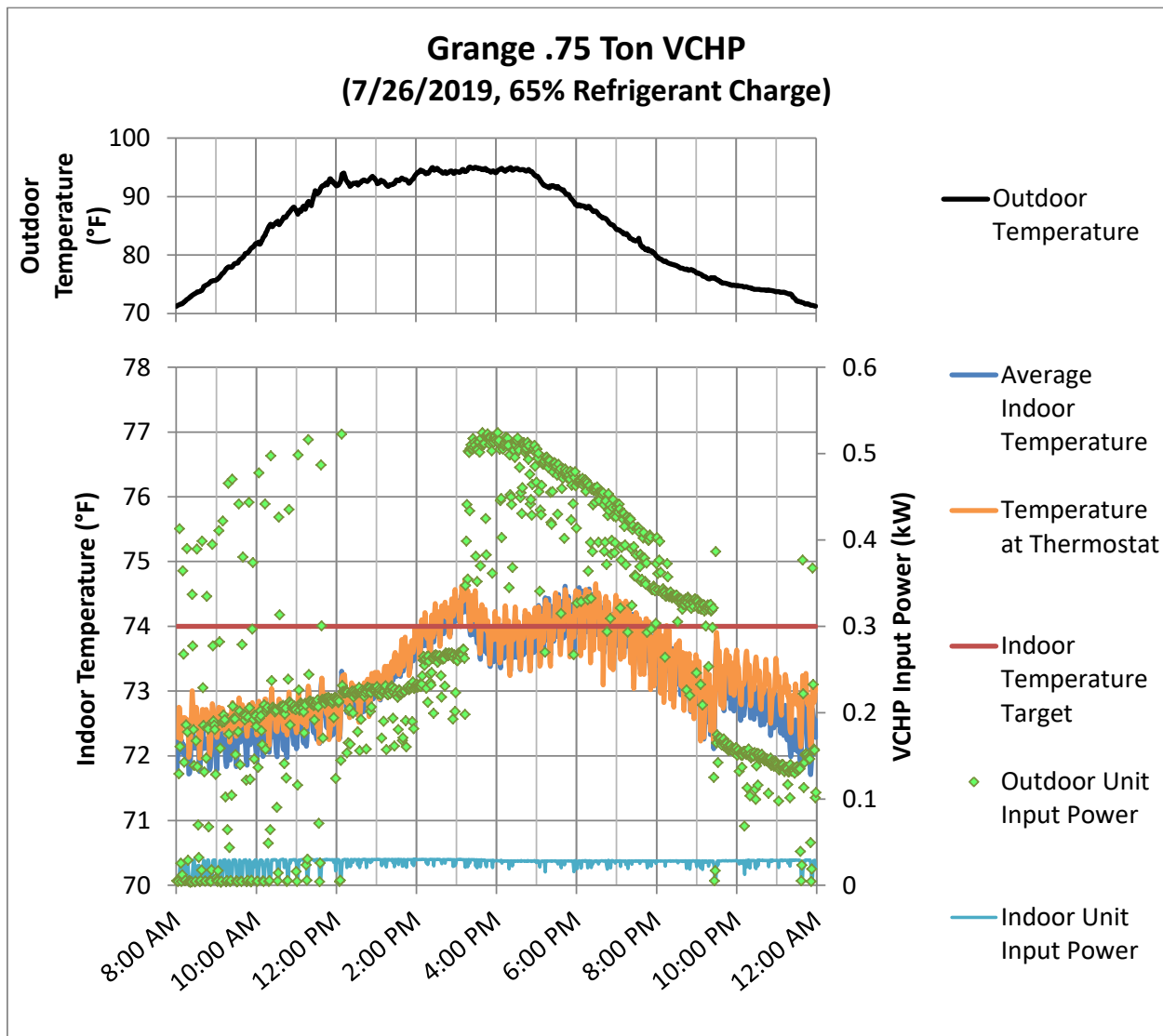


FIGURE 73. GRANGE 0.75 TON VCHP COOLING EXAMPLE, 65% REFRIGERANT CHARGE

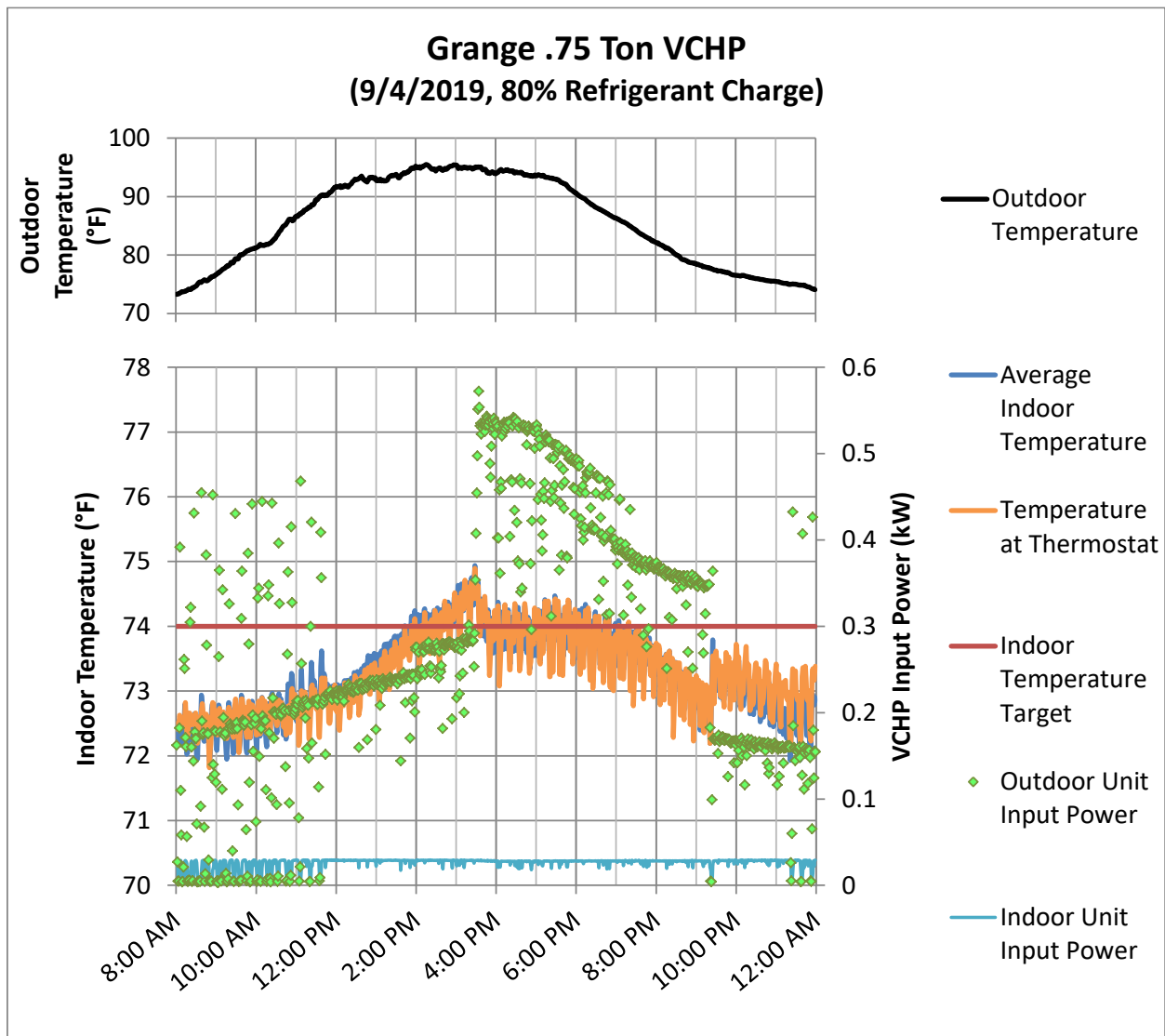


FIGURE 74. GRANGE 0.75 TON VCHP COOLING EXAMPLE, 80% REFRIGERANT CHARGE

Figure 75 plots the 0.75 ton VCHP input power against outdoor temperature at each of the four refrigerant levels. The plotted data includes all days the 0.75 ton VCHP system operated during the 2019 cooling season, and each plotted point represents one minute. The large cluster of data points at about 0.2 kW reflects the system's preferred low speed, while clusters at higher input power levels reflect increased speed/capacity levels. Figure 75 shows that this system operated at higher speeds more frequently at lower refrigerant levels, while at correct refrigerant charge it was able to remain at low speed the majority of the time.

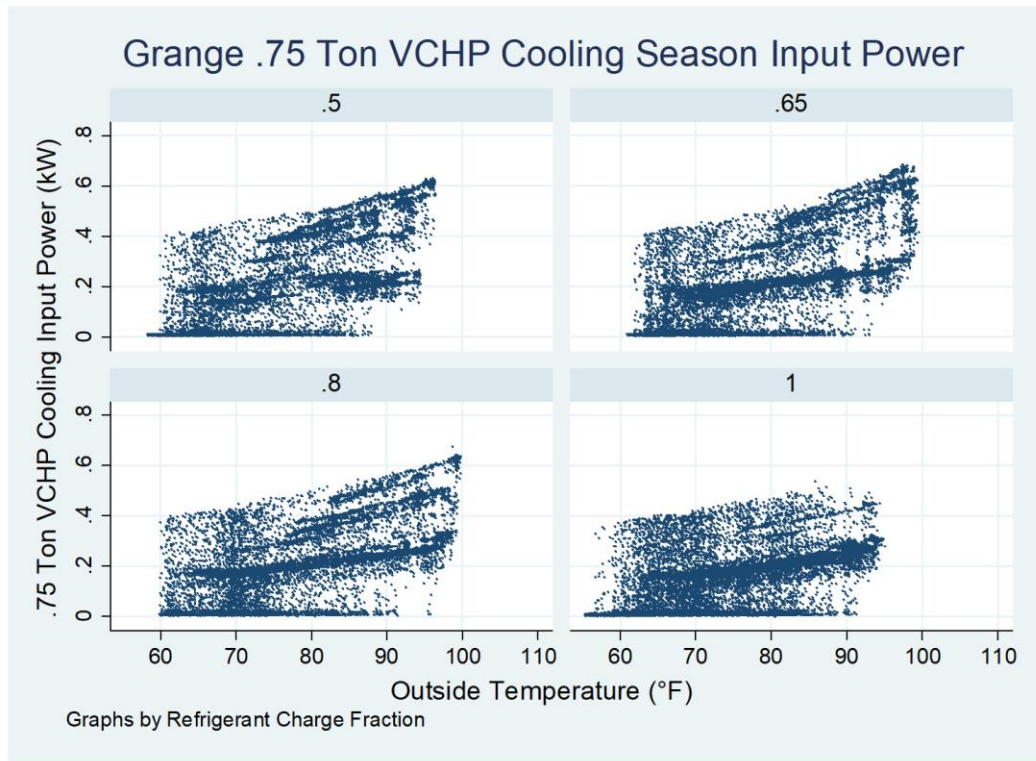


FIGURE 75. GRANGE 0.75 TON VCHP INPUT POWER IN COOLING MODE

Cycling characteristics for the 0.75 ton VCHP at each refrigerant level are tabulated against daily average outdoor temperature in Table 35. This system typically runs a large number of short cycles, exceeding 80 cycles per day on mild days. Low refrigerant charge increased the average cycle length and decreased the number of cycles per day.

TABLE 35. GRANGE 0.75 TON VCHP CYCLING CHARACTERISTICS IN COOLING MODE

	DAILY AVERAGE OUTDOOR TEMPERATURE (°F)	REFRIGERANT LEVEL			
		50%	65%	80%	100%
Average Cycle Length (Minutes)	70	17.7	-	10.2	7.1
	75	16.0	11.8	12.0	11.2
	80	19.3	15.2	13.2	12.6
	85	-	15.6	14.7	-
Average Cycles Per Day	70	50.0	-	87.0	88.3
	75	56.5	79.6	90.0	80.3
	80	55.7	79.5	85.3	83.7
	85	-	72.0	78.5	-

DAILY ENERGY USE

The daily cooling energy use regression results for the 0.75 ton VCHP are shown in Table 36. Figure 76 displays the monitored and regression predicted daily energy use for each refrigerant level. Figure 77 displays the monitored and regression predicted VCHP daily energy use plotted against daily average outdoor temperature, showing that the modeled results produced a VCHP model that closely matches the monitored data.

TABLE 36. GRANGE 0.75 TON VCHP DAILY COOLING ENERGY REGRESSION

SYSTEM	VARIABLE	COEFFICIENT	t	95% CONFIDENCE INTERVAL	
0.75 Ton VCHP	E _{Ref}	0.4902	15.44	0.4258	0.5546
	E _{Ref_R50}	0.2311	8.84	0.1781	0.2842
	E _{Ref_R65}	0.1280	5.20	0.0781	0.1779
	E _{Ref_R80}	0.0773	3.15	0.0275	0.1271
	Constant	0.8965	7.02	0.6376	1.1553
	R ²	0.97			
	Daily Standby kWh	0.23			

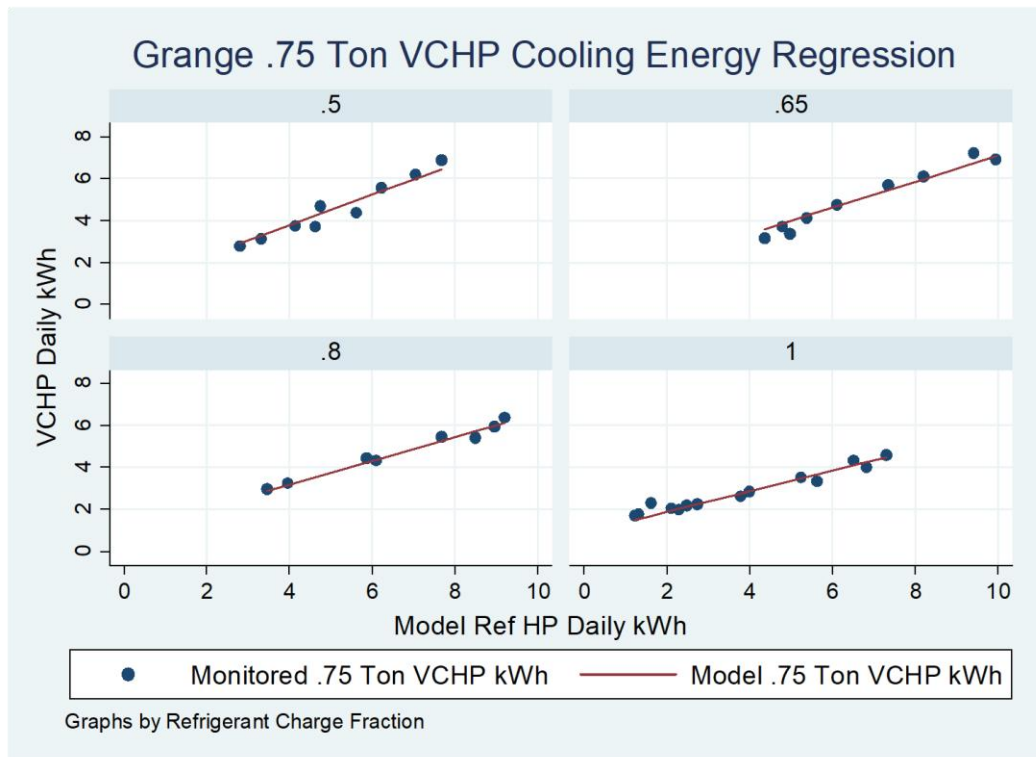


FIGURE 76. GRANGE 0.75 TON VCHP DAILY COOLING ENERGY REGRESSION

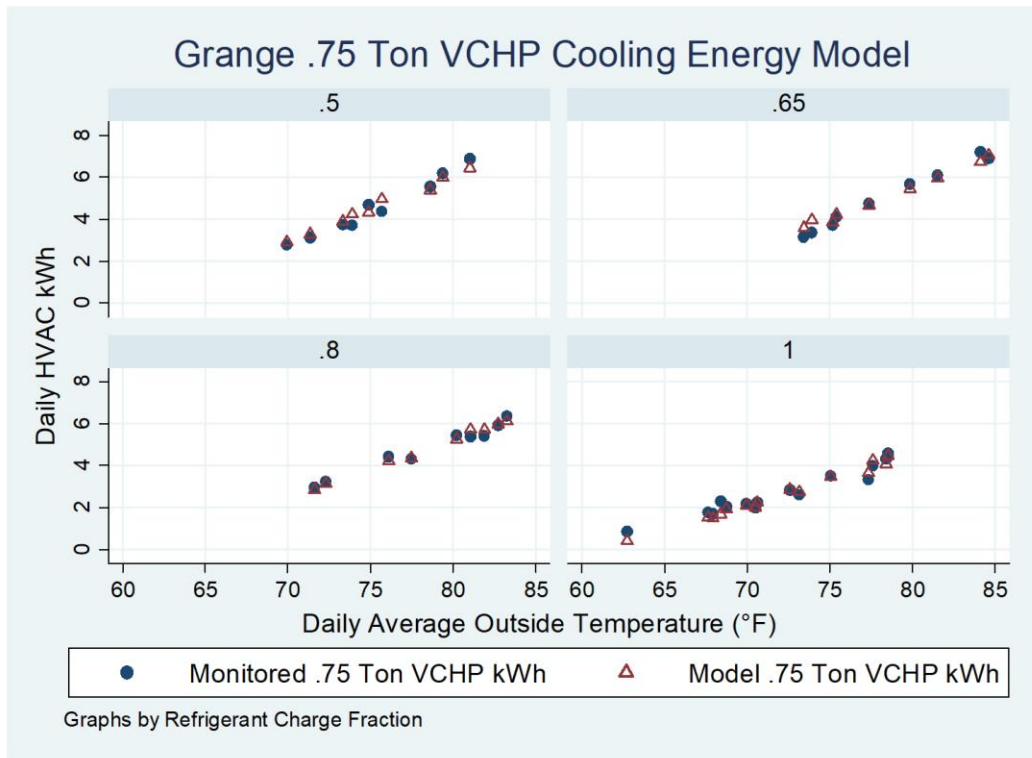


FIGURE 77. GRANGE 0.75 TON VCHP MONITORED AND MODEL PREDICTED DAILY COOLING ENERGY

The regression predicted normalized seasonal energy use estimates are shown in Table 37. The daily energy use analysis shows efficiency reductions at all three refrigerant undercharge levels, with a loss of 24% at 50% refrigerant charge.

TABLE 37. GRANGE 0.75 TON VCHP NORMALIZED COOLING SEASON ENERGY USE

SYSTEM	REFRIGERANT LEVEL	SEASONAL ENERGY USE (kWh)	SEASONAL ENERGY USE RELATIVE TO CORRECT REFRIGERANT CHARGE	IMPLIED EFFICIENCY RELATIVE TO CORRECT REFRIGERANT CHARGE
0.75 Ton VCHP	50%	567.1	131%	76%
	65%	507.6	117%	85%
	80%	478.4	110%	91%
	100%	433.8	100%	100%

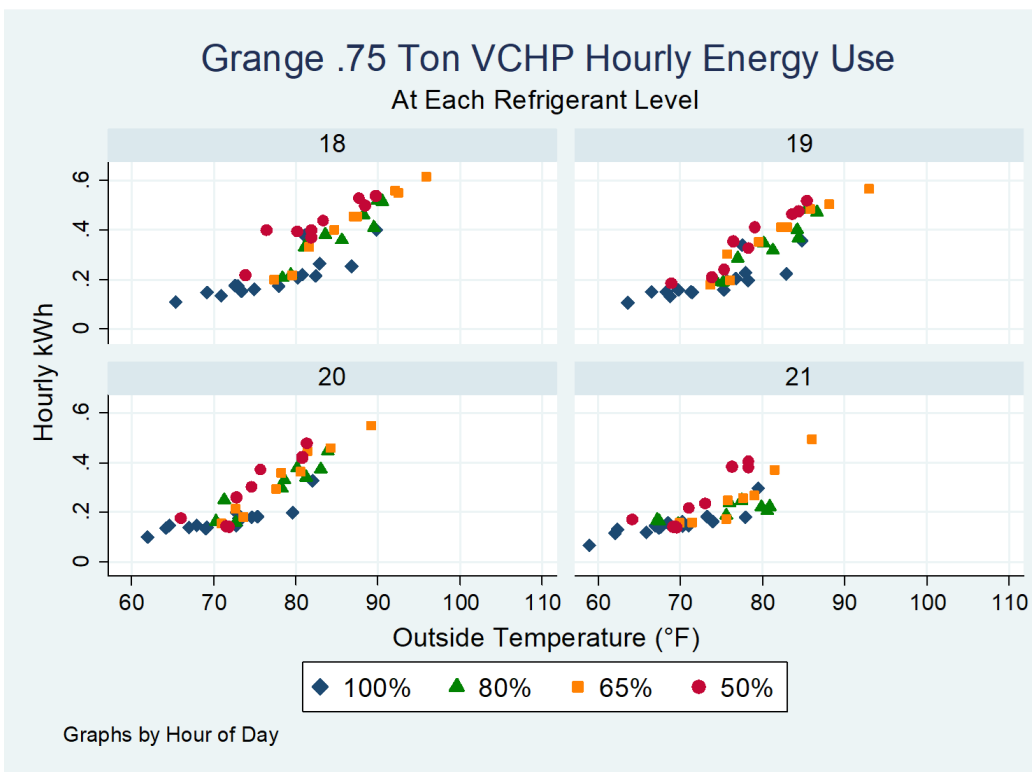
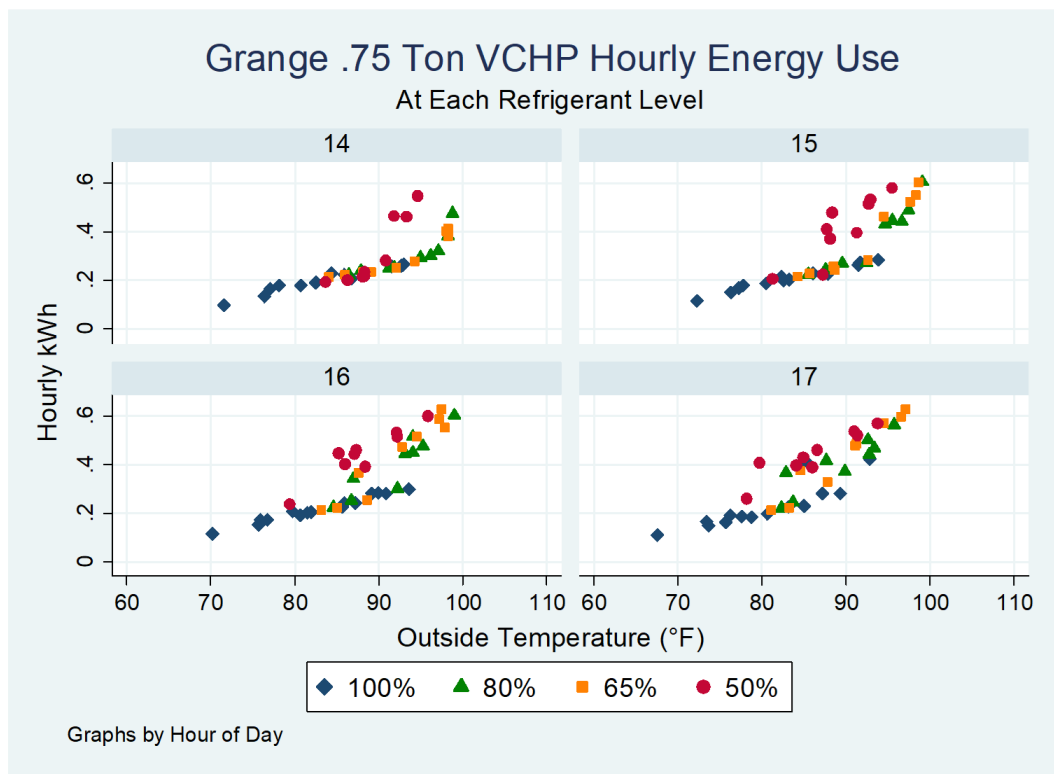
AFTERNOON AND EVENING DEMAND

Refrigerant undercharge had a large effect on afternoon and evening demand of the 0.75 ton VCHP. Because the VCHP needed to operate at higher compressor speeds to meet the cooling load on hot afternoons when undercharged, demand during hot afternoon hours increased by as much as 90%. Average hourly demand relative to performance at correct refrigerant charge is tabulated in Table 38. The monitored energy use during each hour for each refrigerant level is plotted in Figure 78.

Evening demand was more impacted by low refrigerant charge than daily energy use in part because of differences in how indoor temperature was controlled throughout the day. With correct refrigerant charge, indoor temperatures were maintained below target later into the afternoon, effectively shifting some of the evening load to the morning and early afternoon hours. With low refrigerant charge, indoor temperatures exceeded target earlier in the day, resulting in higher loads in the afternoon and evening. This behavior is illustrated in Figure 71 and Figure 72. With correct refrigerant charge indoor temperatures were maintained below target until 4 PM. With 50% refrigerant charge indoor temperatures exceeded target at 12:30 PM and the system had to operate at higher compressor speeds to meet the cooling load in the afternoon and evening.

TABLE 38. GRANGE 0.75 TON VCHP AVERAGE HOURLY DEMAND RELATIVE TO PERFORMANCE AT CORRECT REFRIGERANT CHARGE

REFRIGERANT LEVEL	HOUR	HOURLY AVERAGE OUTDOOR TEMPERATURE (°F)				
		80	85	90	95	100
50%	2-3 PM	-	92%	114%	191%	-
	3-4 PM	105%	106%	162%	191%	-
	4-5 PM	118%	185%	170%	199%	-
	5-6 PM	176%	151%	188%	134%	-
	6-7 PM	162%	168%	130%	-	-
	7-8 PM	144%	168%	-	-	-
	8-9 PM	167%	-	-	-	-
	9-10 PM	165%	-	-	-	-
65%	2-3 PM	-	102%	98%	106%	-
	3-4 PM	-	105%	98%	131%	-
	4-5 PM	-	92%	110%	183%	-
	5-6 PM	113%	108%	154%	142%	-
	6-7 PM	115%	166%	130%	-	-
	7-8 PM	149%	156%	-	-	-
	8-9 PM	139%	-	-	-	-
	9-10 PM	125%	-	-	-	-
80%	2-3 PM	-	104%	100%	116%	-
	3-4 PM	-	107%	102%	159%	-
	4-5 PM	-	115%	106%	157%	-
	5-6 PM	117%	110%	141%	117%	-
	6-7 PM	106%	143%	118%	-	-
	7-8 PM	130%	149%	-	-	-
	8-9 PM	128%	-	-	-	-
	9-10 PM	91%	-	-	-	-

**FIGURE 78. GRANGE 0.75 TON VCHP COOLING SEASON HOURLY ENERGY USE AT EACH REFRIGERANT LEVEL**

HEATING SEASON

The 0.75 ton VCHP system maintained similar indoor temperatures at all refrigerant levels. Average temperatures of each room relative to the target temperature are shown in Figure 79. Average indoor temperatures relative to the temperatures at correct refrigerant charge are shown in Figure 80. The plotted values represent the average of all minutes that occurred during hours with compressor operation during the hour, indicating that the system was providing heating to the house during the hour. This system is controlled by a single thermostat located in the kitchen.

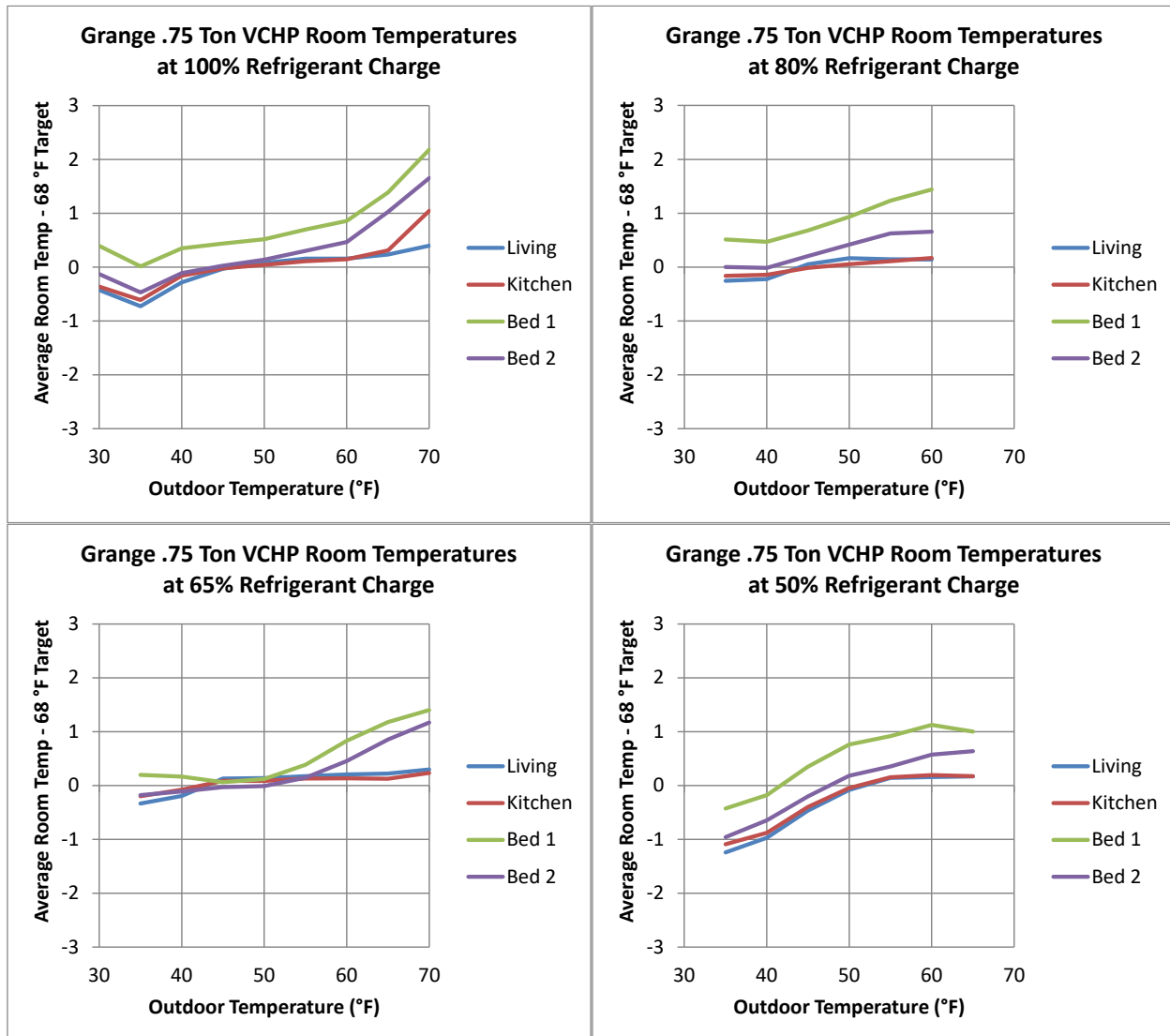


FIGURE 79. GRANGE 0.75 TON VCHP HEATING SEASON INDOOR TEMPERATURE DELTA TO TARGET

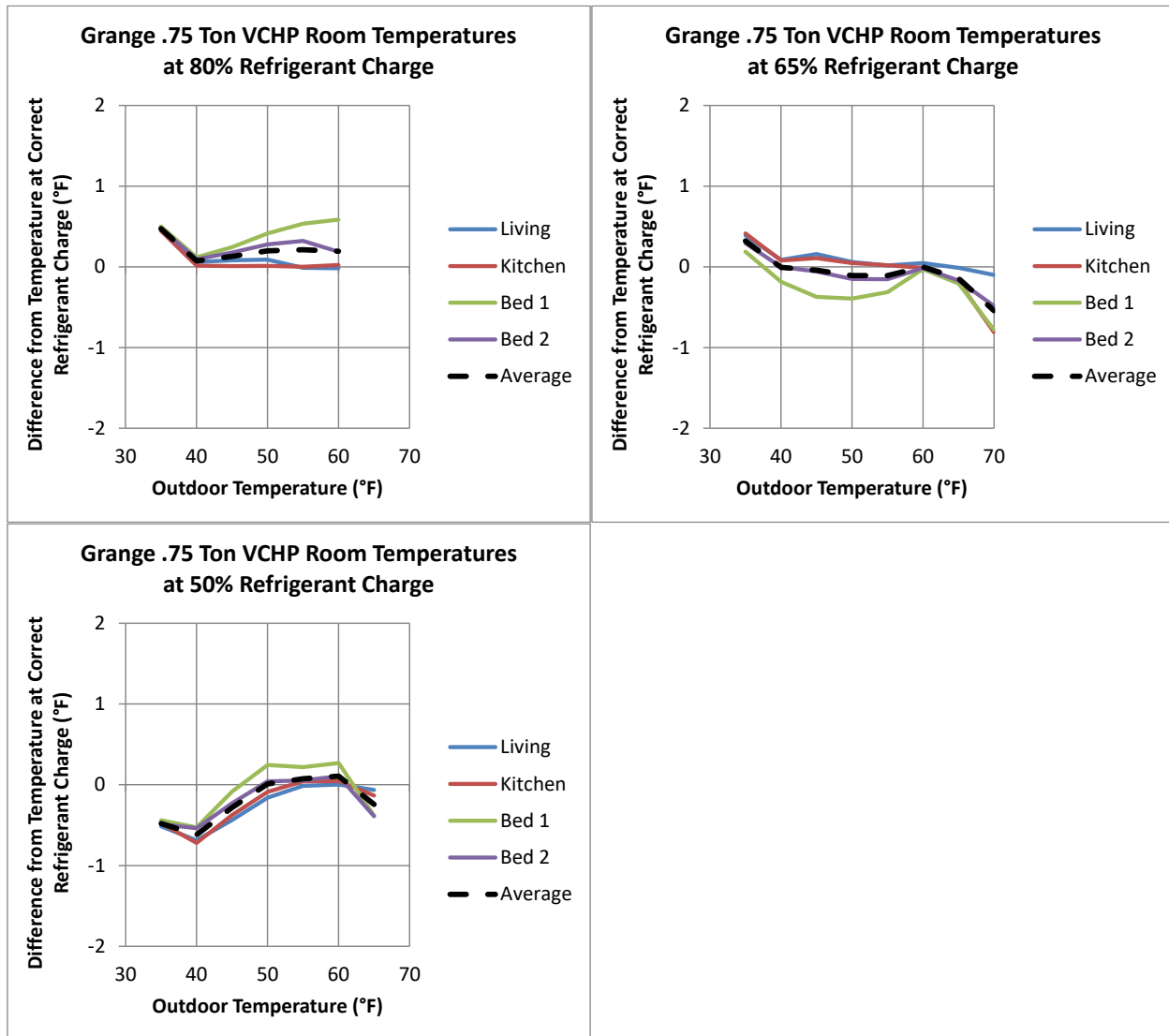


FIGURE 80. GRANGE 0.75 TON VCHP HEATING SEASON INDOOR TEMPERATURES AT REFRIGERANT UNDERCHARGE CONDITIONS RELATIVE TO TEMPERATURES AT CORRECT REFRIGERANT CHARGE

Figure 81 and Figure 82 show examples of how this system operated on days with similar outdoor temperature at correct refrigerant charge and at 50% refrigerant charge. Each plotted point represents one minute.

The system operated at lower input power and maintained indoor temperatures closer to target on the day with correct refrigerant charge.

The brief period of high input power at 7:30 AM on the day with correct refrigerant charge is a defrost cycle. Defrost operation was infrequent, with only 11 defrost cycles observed during the winter, occurring only on the coldest days. There was no observed relationship between refrigerant levels and defrost.

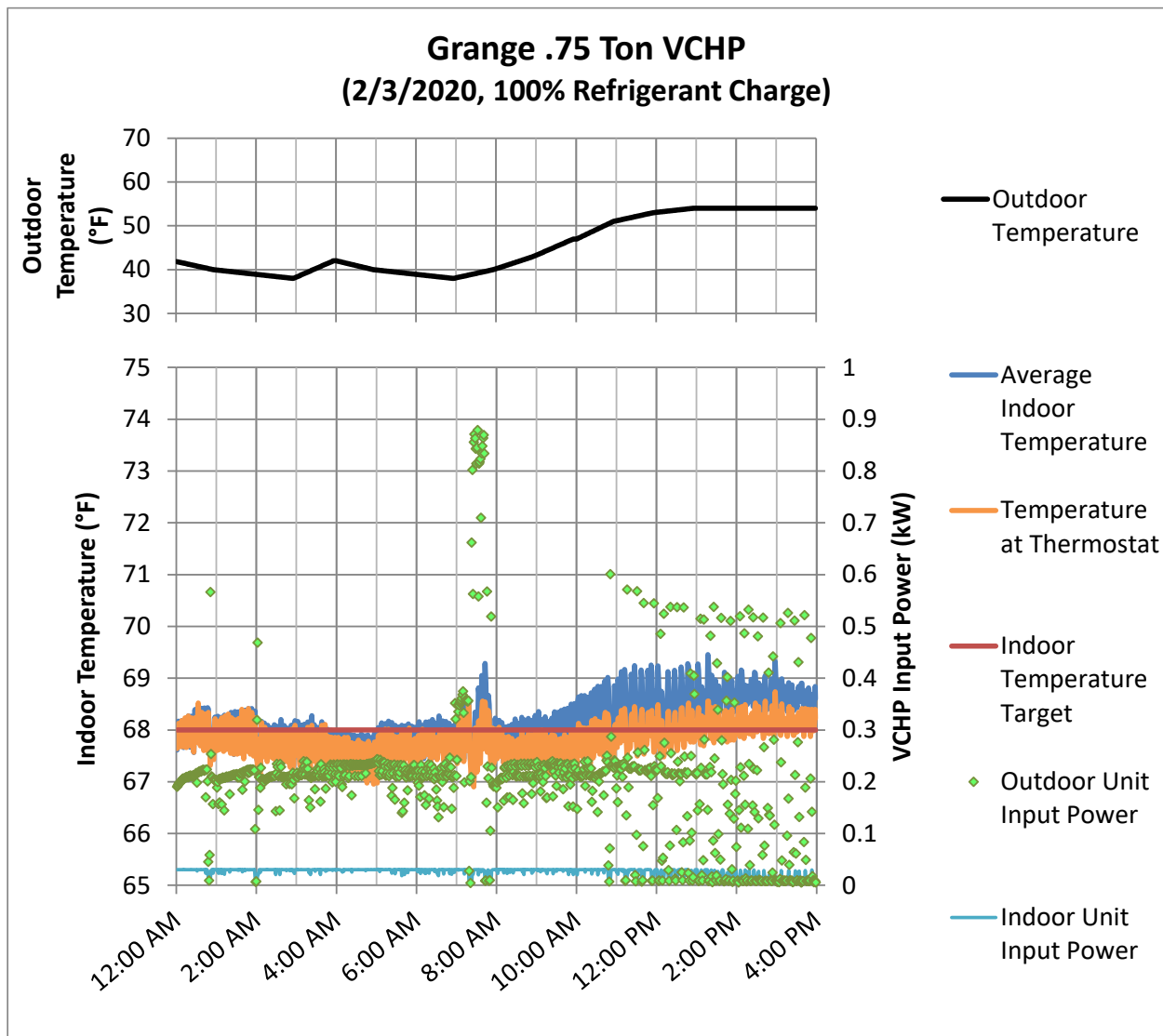


FIGURE 81. GRANGE 0.75 TON VCHP HEATING EXAMPLE, CORRECT REFRIGERANT CHARGE

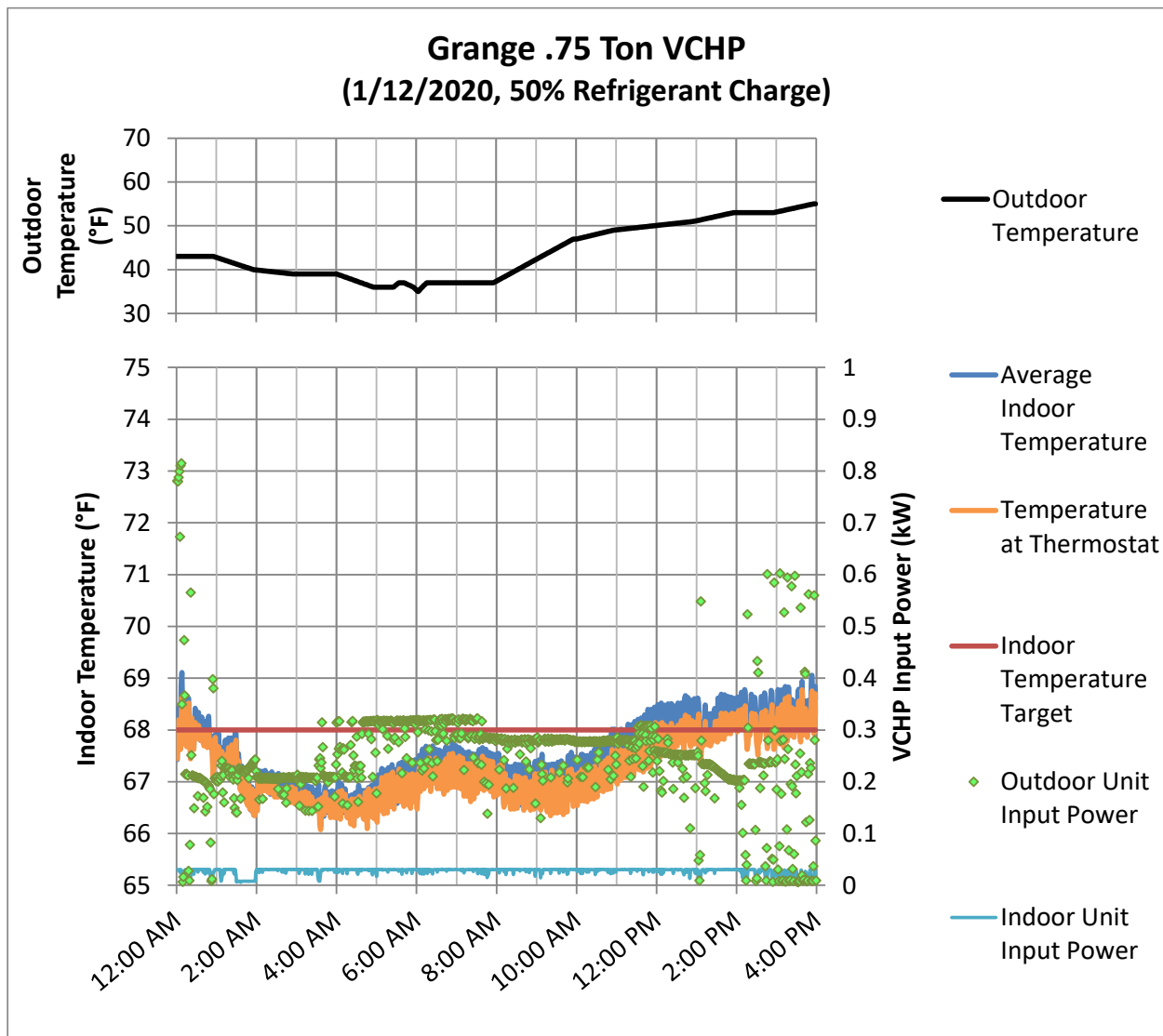


FIGURE 82. GRANGE 0.75 TON VCHP HEATING EXAMPLE, 50% REFRIGERANT CHARGE

Figure 83 and Figure 84 show days at 65% and 80% refrigerant charge. The 65% day is warmer due to mild weather throughout the 65% testing period.

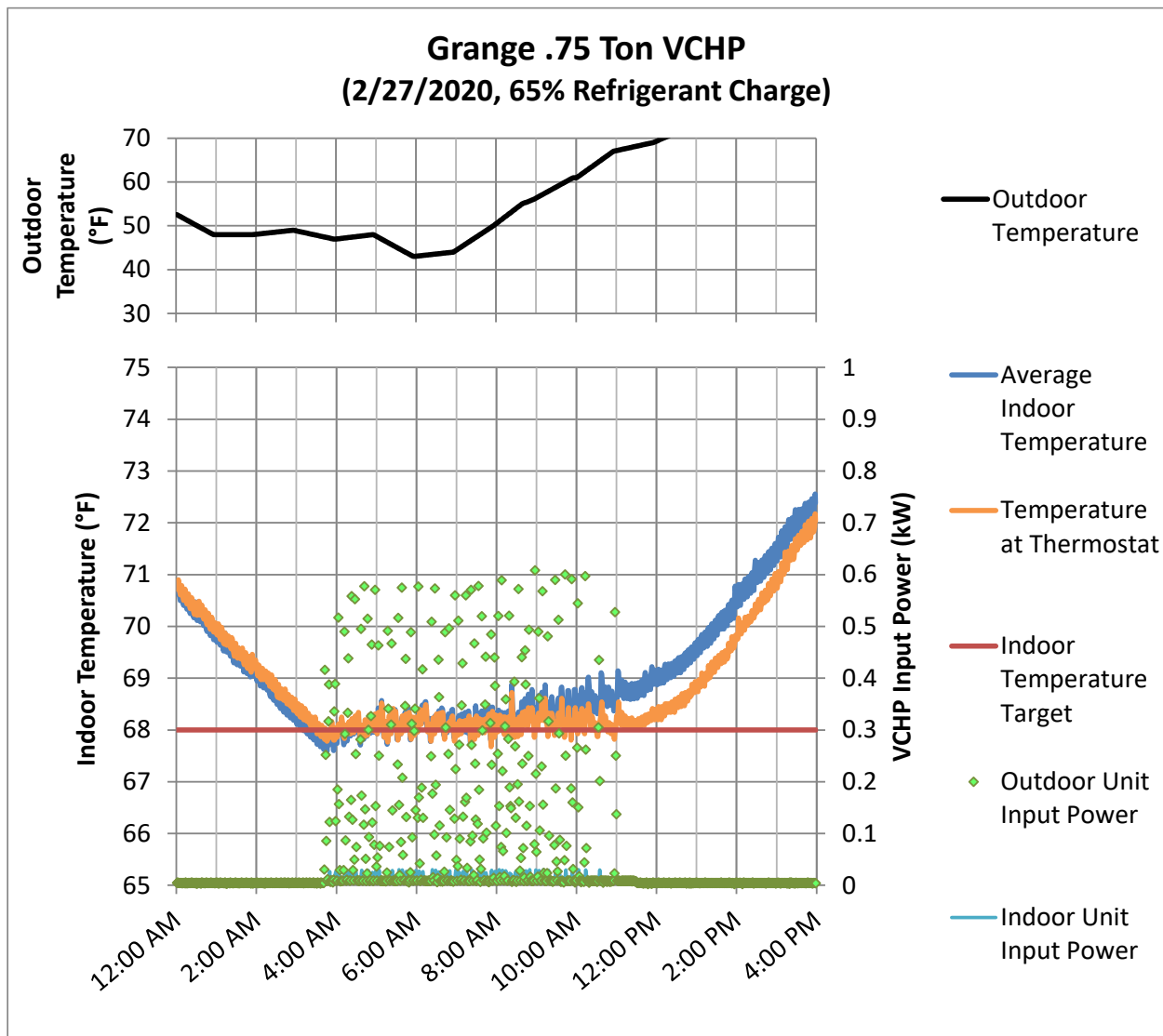


FIGURE 83. GRANGE 0.75 TON VCHP HEATING EXAMPLE, 65% REFRIGERANT CHARGE

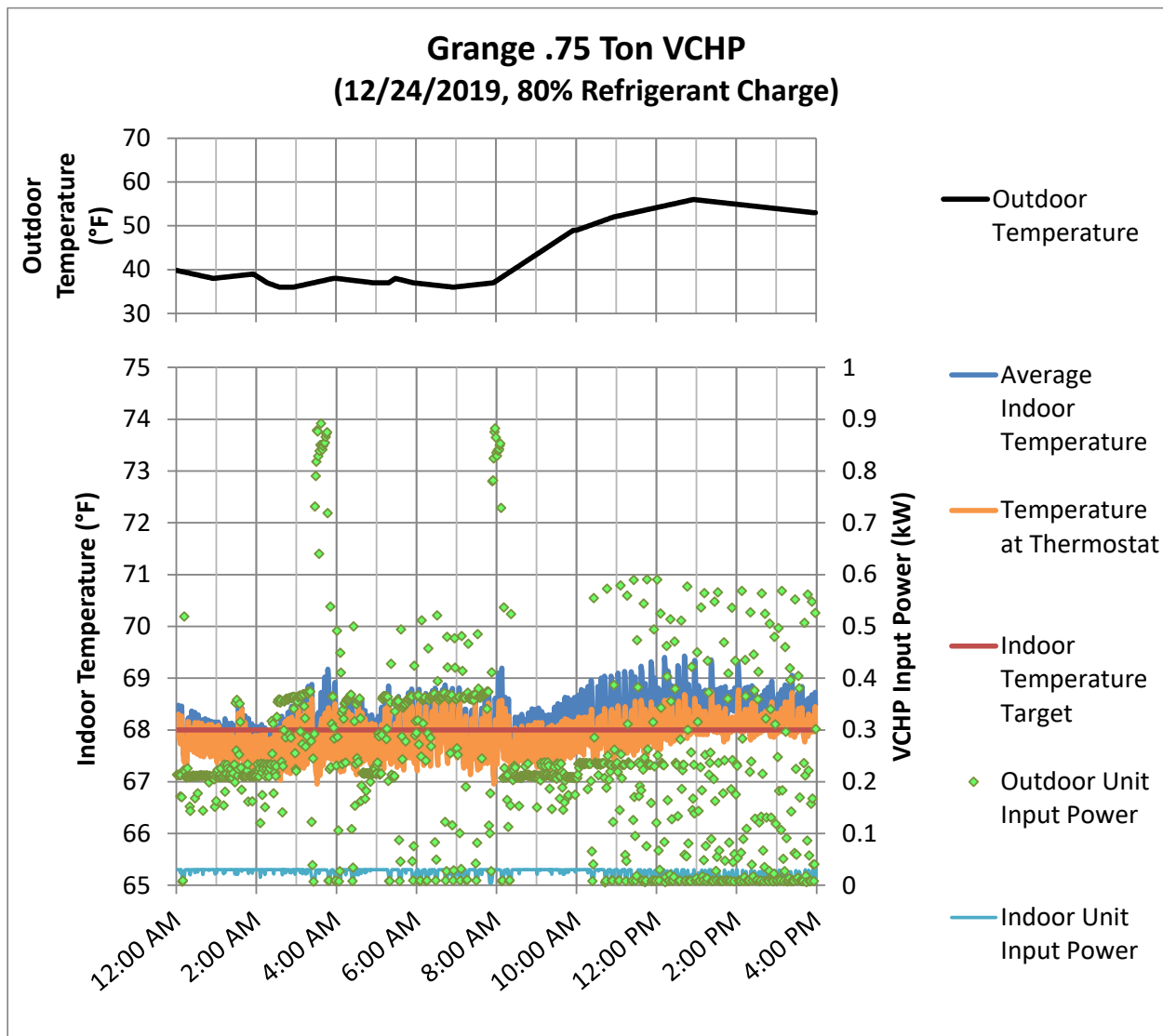


FIGURE 84. GRANGE 0.75 TON VCHP HEATING EXAMPLE, 80% REFRIGERANT CHARGE

Figure 85 plots the 0.75 ton VCHP input power against outdoor temperature at each of the four refrigerant levels. The plotted data includes all days the 0.75 ton VCHP system operated during the 2019-2020 heating season, and each plotted point represents one minute. The large cluster of data points at about 0.2 kW reflects the system's preferred low speed. The days plotted were as closely matched as possible, but the 65% refrigerant charge day was warmer due to lack of cold weather during the monitoring period.

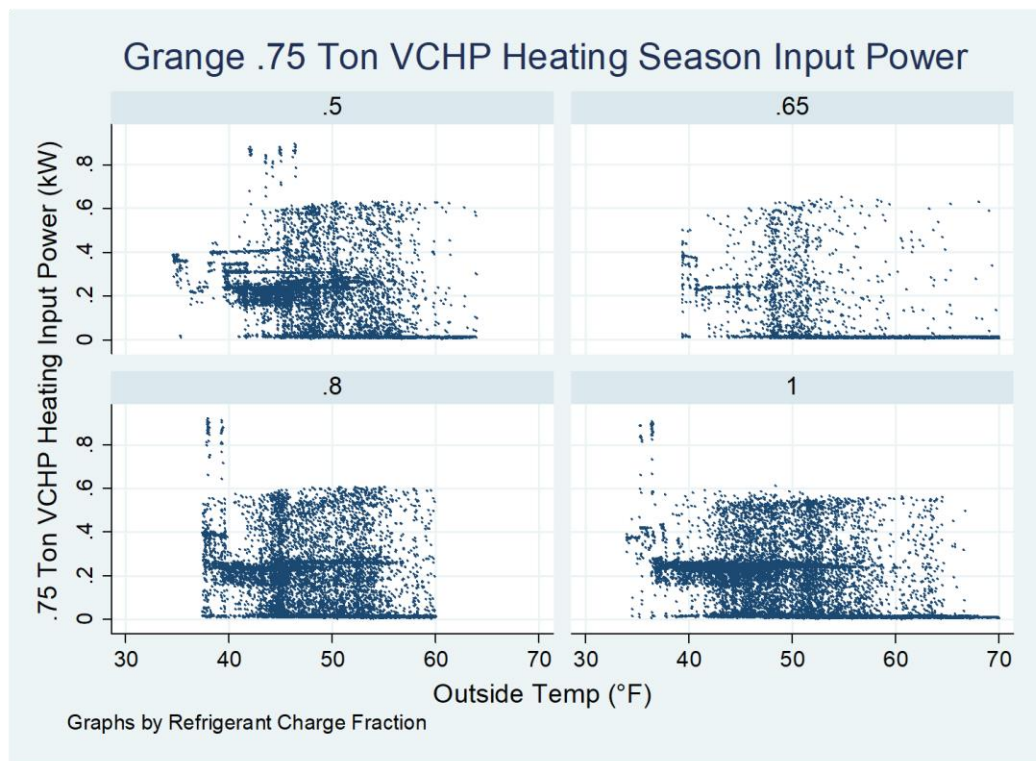


FIGURE 85. GRANGE 0.75 TON VCHP INPUT POWER IN HEATING MODE

Cycling characteristics for the 0.75 ton VCHP at each refrigerant level are tabulated against daily average outdoor temperature in Table 39. This system typically runs a large number of short cycles, often exceeding 100 cycles per day. There is no clear relationship between refrigerant levels and cycling behavior.

TABLE 39. GRANGE 0.75 TON VCHP CYCLING CHARACTERISTICS IN HEATING MODE

	DAILY AVERAGE OUTDOOR TEMPERATURE (°F)	REFRIGERANT LEVEL			
		50%	65%	80%	100%
Average Cycle Length (Minutes)	45	29.6	-	8.4	11.0
	50	7.2	10.7	6.7	8.1
	55	4.6	3.7	-	4.1
	60	-	2.9	-	2.9
Average Cycles Per Day	45	67.4	-	117.8	110.3
	50	75.0	34.0	136.3	78.8
	55	102.5	47.0	-	118.1
	60	-	51.3	-	63.5

DAILY ENERGY USE

The daily heating energy use regression results for the 0.75 ton VCHP are shown in Table 40. Figure 86 displays the monitored and regression predicted daily energy use for each refrigerant level. Figure 87 displays the monitored and regression predicted VCHP daily energy use plotted against daily average outdoor temperature, comparing the modeled results to directly monitored data.

TABLE 40. GRANGE .75 TON VCHP DAILY HEATING ENERGY REGRESSION

SYSTEM	VARIABLE	COEFFICIENT	t	95% CONFIDENCE INTERVAL	
.75 Ton VCHP	E _{Ref}	0.1841	15.50	0.1600	0.2082
	E _{Ref_R50}	0.0249	2.36	0.0035	0.0463
	E _{Ref_R65}	-0.0387	-1.47	-0.0919	0.0146
	E _{Ref_R80}	0.0044	0.42	-0.0166	0.0254
	Constant	0.6927	5.16	0.4203	0.9651
	R ²	0.94			
	Daily Standby kWh	0.34			

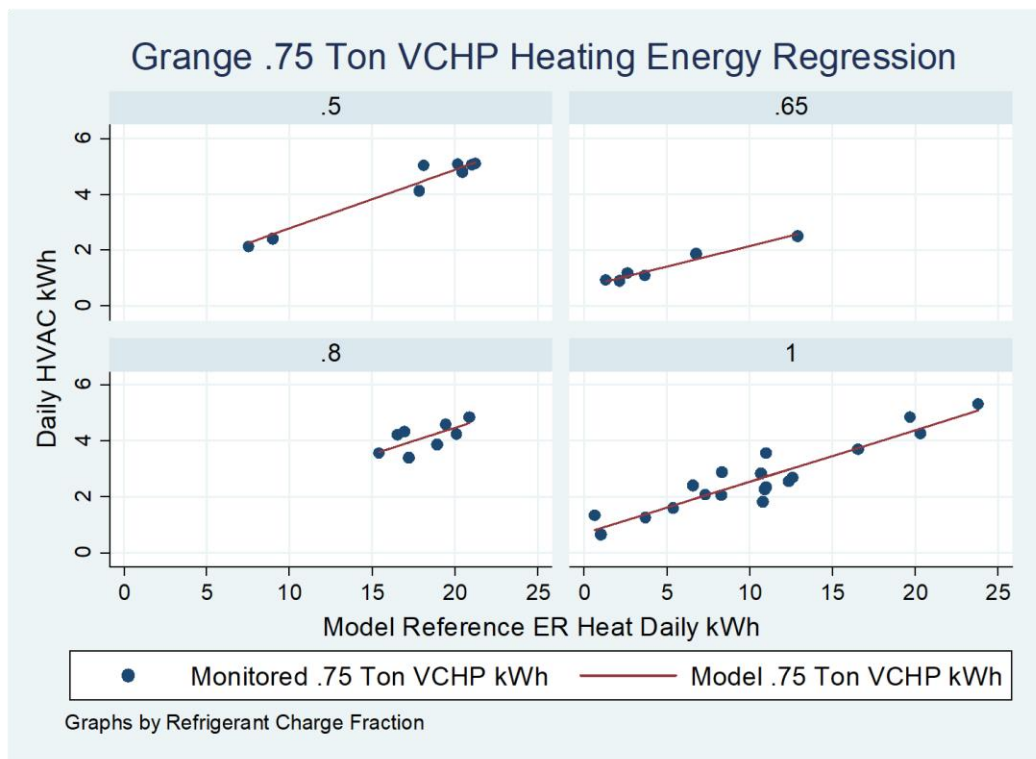


FIGURE 86. GRANGE 0.75 TON VCHP DAILY HEATING ENERGY REGRESSION

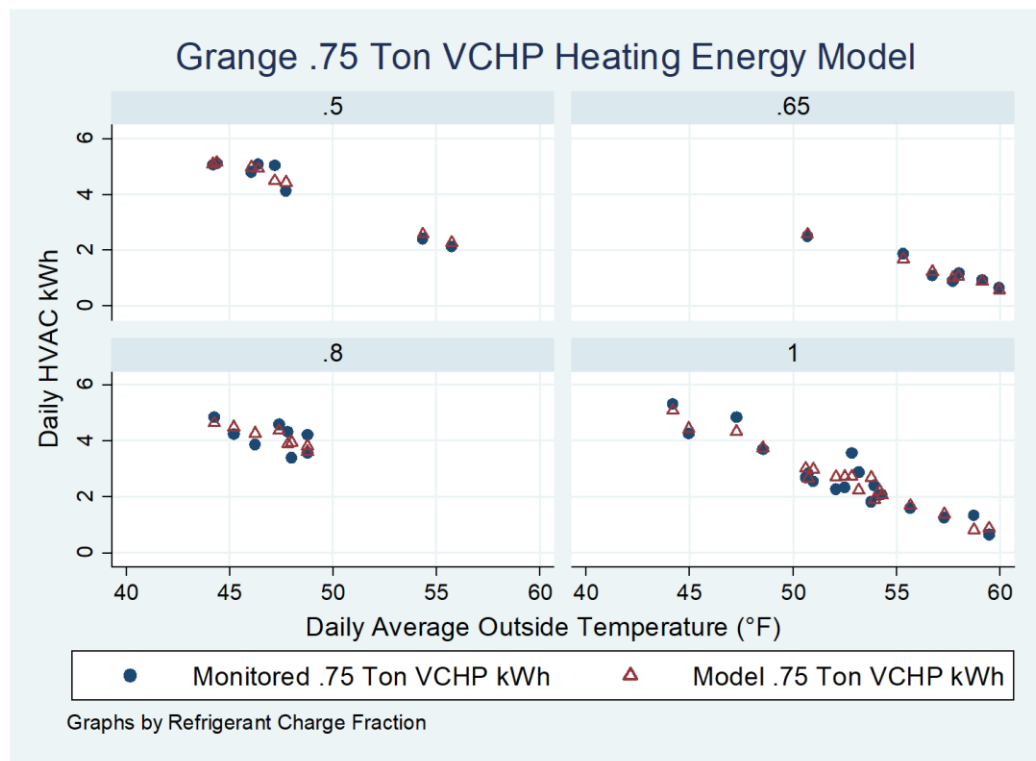


FIGURE 87. GRANGE 0.75 TON VCHP MONITORED AND MODEL PREDICTED DAILY HEATING ENERGY

The regression predicted normalized seasonal energy use estimates are shown in Table 41. The daily energy use analysis shows an efficiency reduction at 50% refrigerant charge but little or no loss at lower undercharge levels. Confidence in the 65% refrigerant charge result is lower than the other refrigerant levels due to warmer weather and very low heating loads throughout the 65% monitoring period. The study did not find evidence of heating efficiency loss at 65% undercharge, but it is possible that the apparent efficiency gain would not occur at higher heating loads.

TABLE 41. GRANGE 0.75 TON VCHP NORMALIZED HEATING SEASON ENERGY USE

SYSTEM	REFRIGERANT LEVEL	SEASONAL ENERGY USE (kWh)	SEASONAL ENERGY USE RELATIVE TO CORRECT REFRIGERANT CHARGE	IMPLIED EFFICIENCY RELATIVE TO CORRECT REFRIGERANT CHARGE
0.75 Ton VCHP	50%	723.2	110%	91%
	65%	560.4	85%	118%
	80%	670.7	102%	98%
	100%	659.4	100%	100%

GRANGE HOUSE, 1 Ton VCHP

COOLING SEASON

The 1 ton VCHP system maintained similar indoor temperatures at all but the lowest refrigerant level. Indoor temperatures increased by about 1.5 °F in on hot afternoons at 50% undercharge.

Average temperatures of each room relative to the target temperature are shown in Figure 88. Average indoor temperatures relative to the temperatures at correct refrigerant charge are shown in Figure 89. The plotted values represent the average of all minutes that occurred during hours with compressor operation during the hour, indicating that the system was providing cooling to the house during the hour. This system is controlled by a single thermostat located in the kitchen.

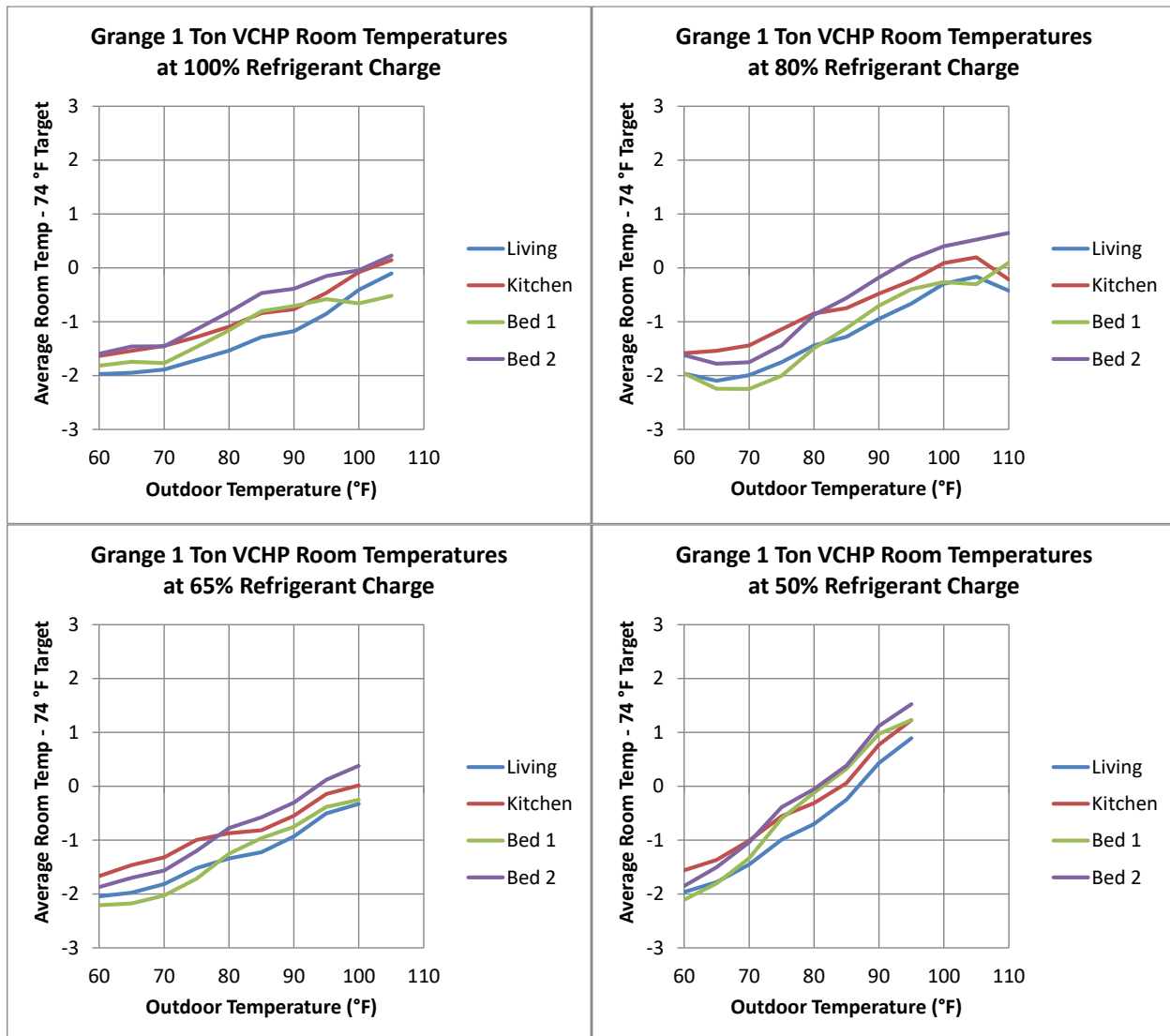


FIGURE 88. GRANGE 1 TON VCHP COOLING SEASON INDOOR TEMPERATURE DELTA TO TARGET

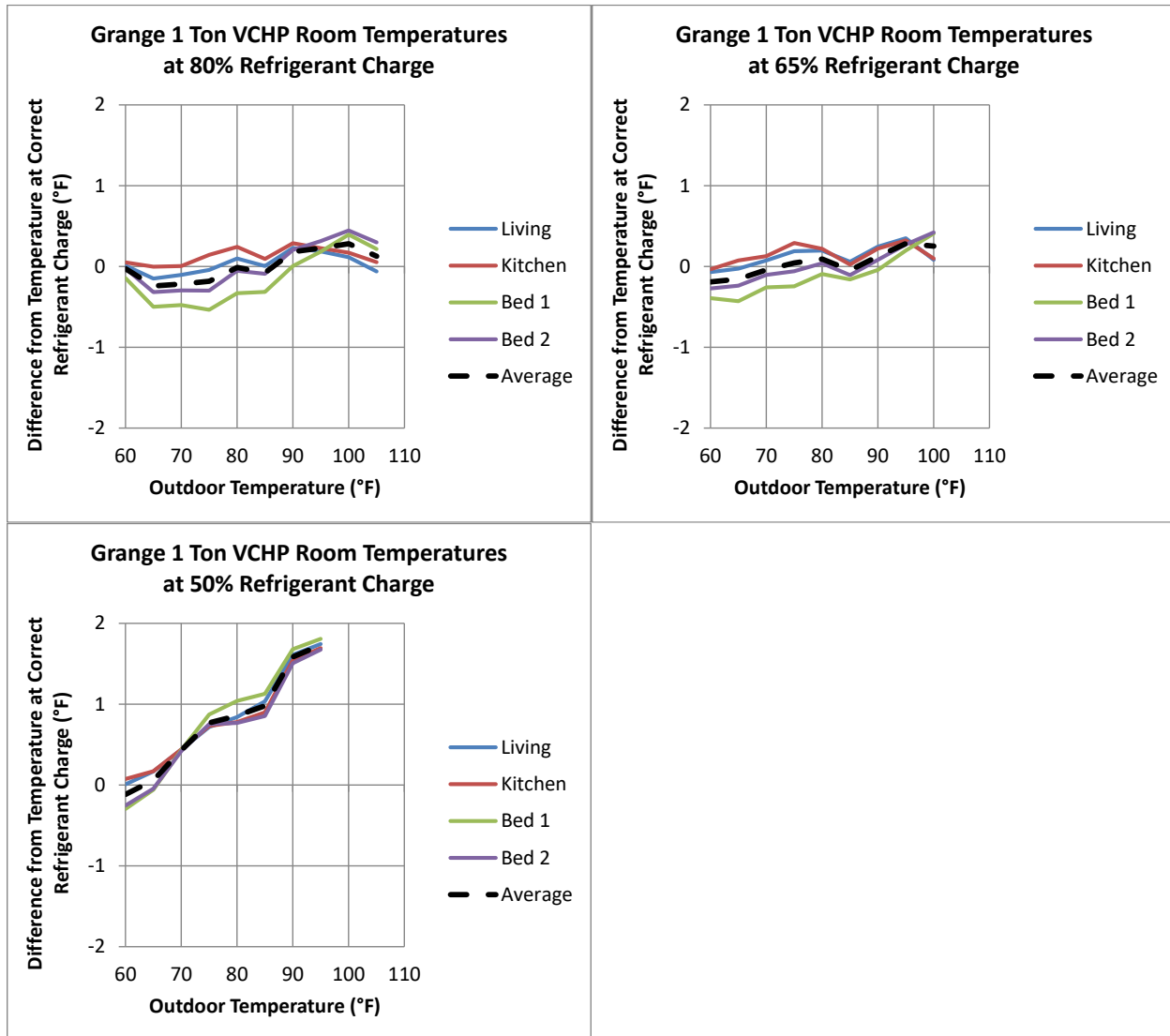


FIGURE 89. GRANGE 1 TON VCHP COOLING SEASON INDOOR TEMPERATURES AT REFRIGERANT UNDERCHARGE CONDITIONS RELATIVE TO TEMPERATURES AT CORRECT REFRIGERANT CHARGE

Figure 90 and Figure 91 show examples of how this system operated on days with similar outdoor temperature at correct refrigerant charge and at 50% refrigerant charge. Each plotted point represents one minute.

In the morning of both days, when outdoor temperatures were mild and cooling loads were low, the system cycled and maintained indoor temperatures about 1.5 °F below target. The scattering of higher outdoor unit input power data points during the morning hours reflects that this system began each cycle with capacity increasing to higher than the minimum level before returning to a lower speed. As outdoor temperature warmed and cooling loads increased, the system settled into constant low speed operation. When indoor temperatures began to exceed target,

outdoor unit power increased indicating that the unit increased compressor speed to deliver more cooling capacity. In the late evening, the system returned to low speed.

Figure 90 and Figure 91 show that low refrigerant charge resulted in compressor speed increasing earlier in the day, increasing to a higher level, and higher speed operation continuing for a longer period of time than at correct refrigerant charge. Indoor temperatures were not as well controlled at 50% refrigerant charge as at correct charge.

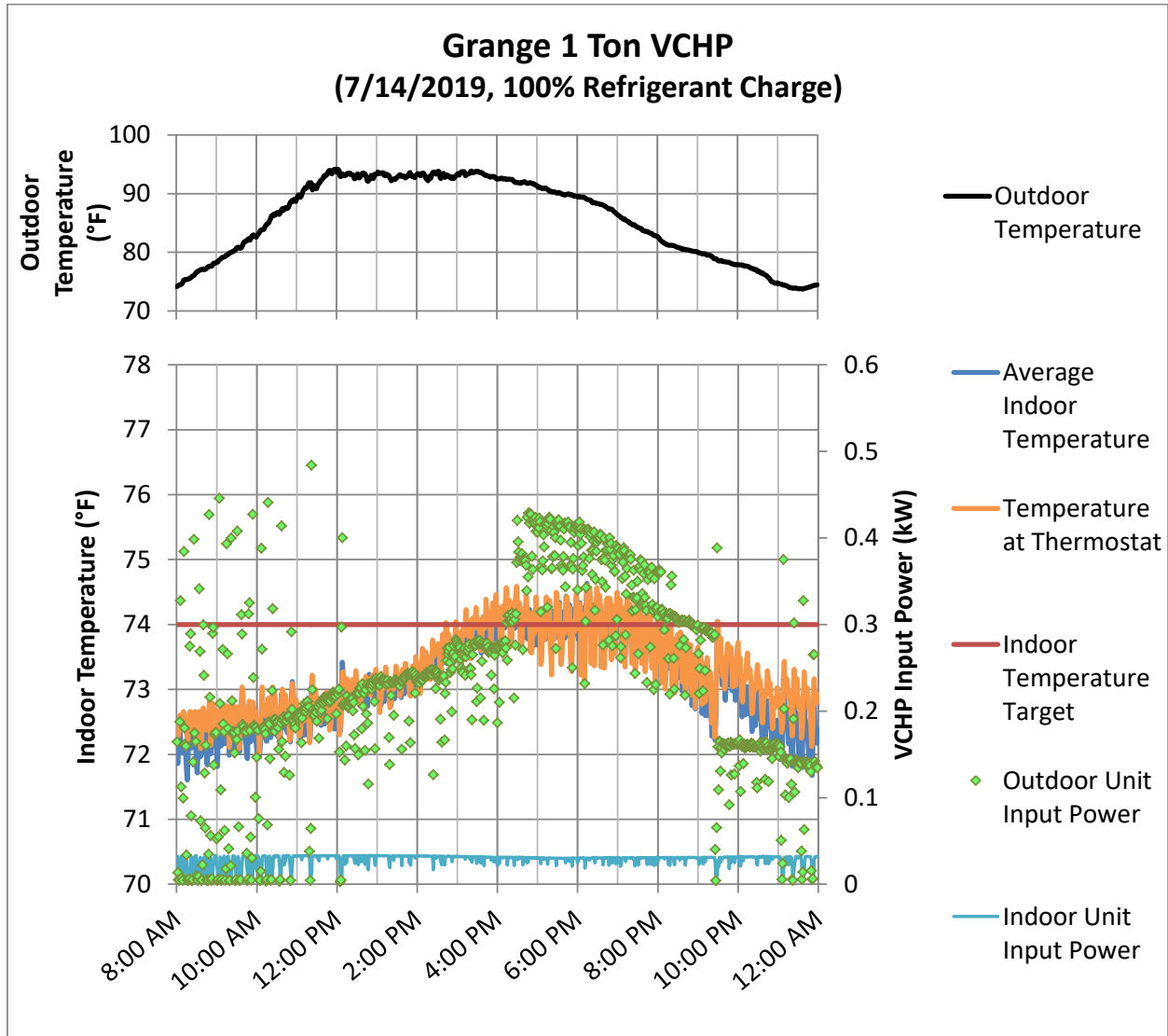


FIGURE 90. GRANGE 1 TON VCHP COOLING EXAMPLE, CORRECT REFRIGERANT CHARGE

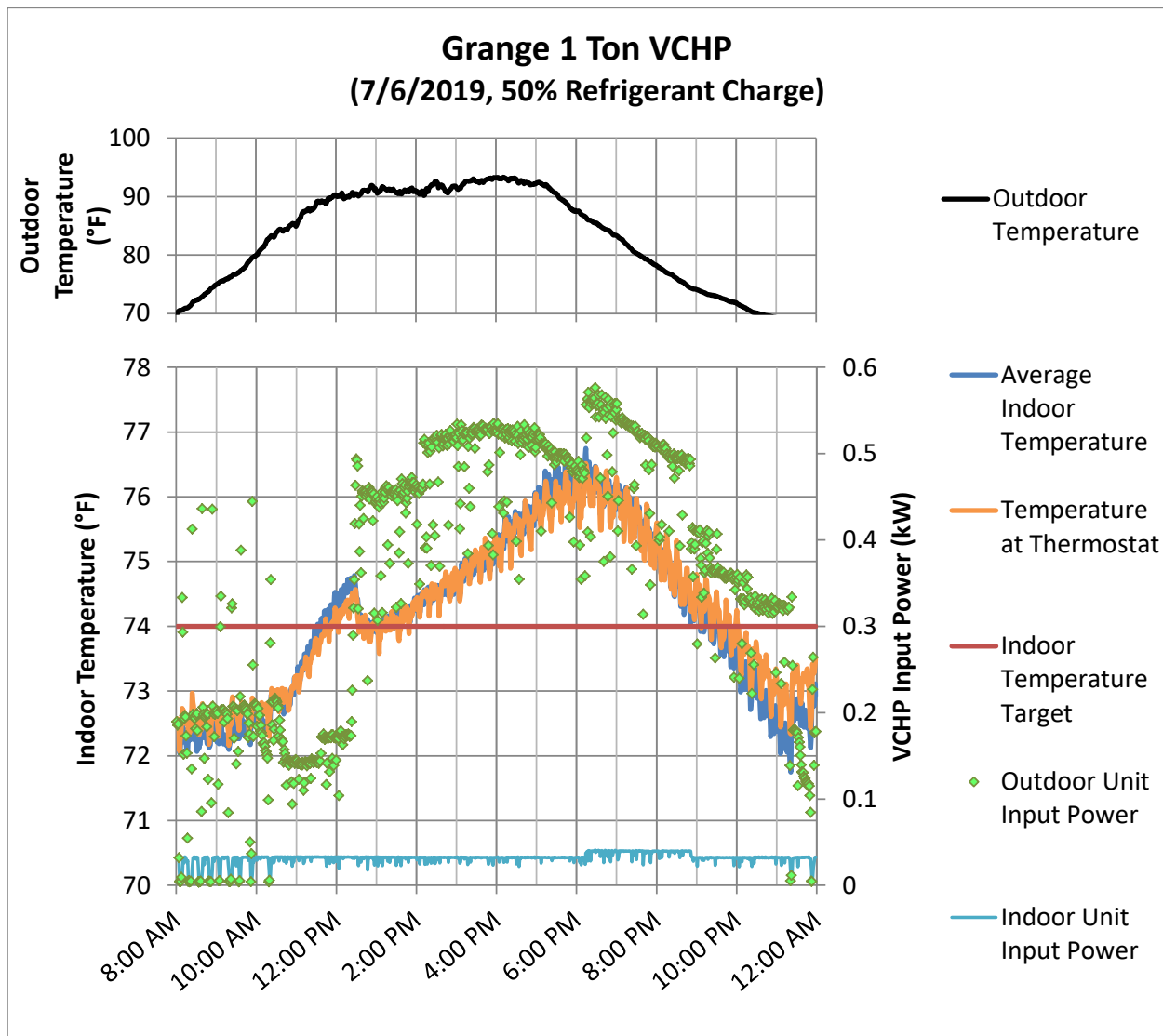


FIGURE 91. GRANGE 1 TON VCHP COOLING EXAMPLE, 50% REFRIGERANT CHARGE

Figure 92 and Figure 93 show similar days with 65% and 80% refrigerant charge.

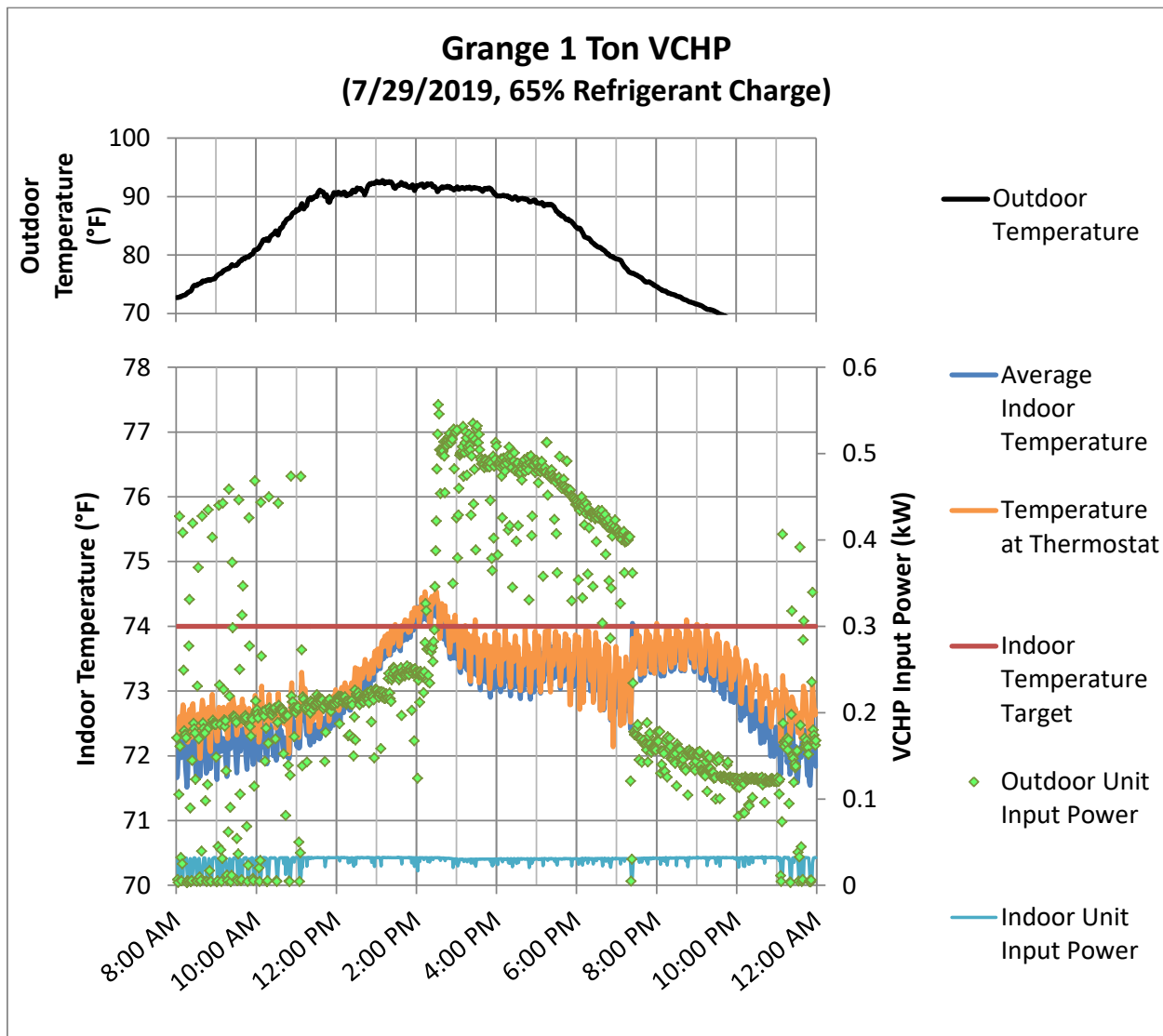


FIGURE 92. GRANGE 1 TON VCHP COOLING EXAMPLE, 65% REFRIGERANT CHARGE

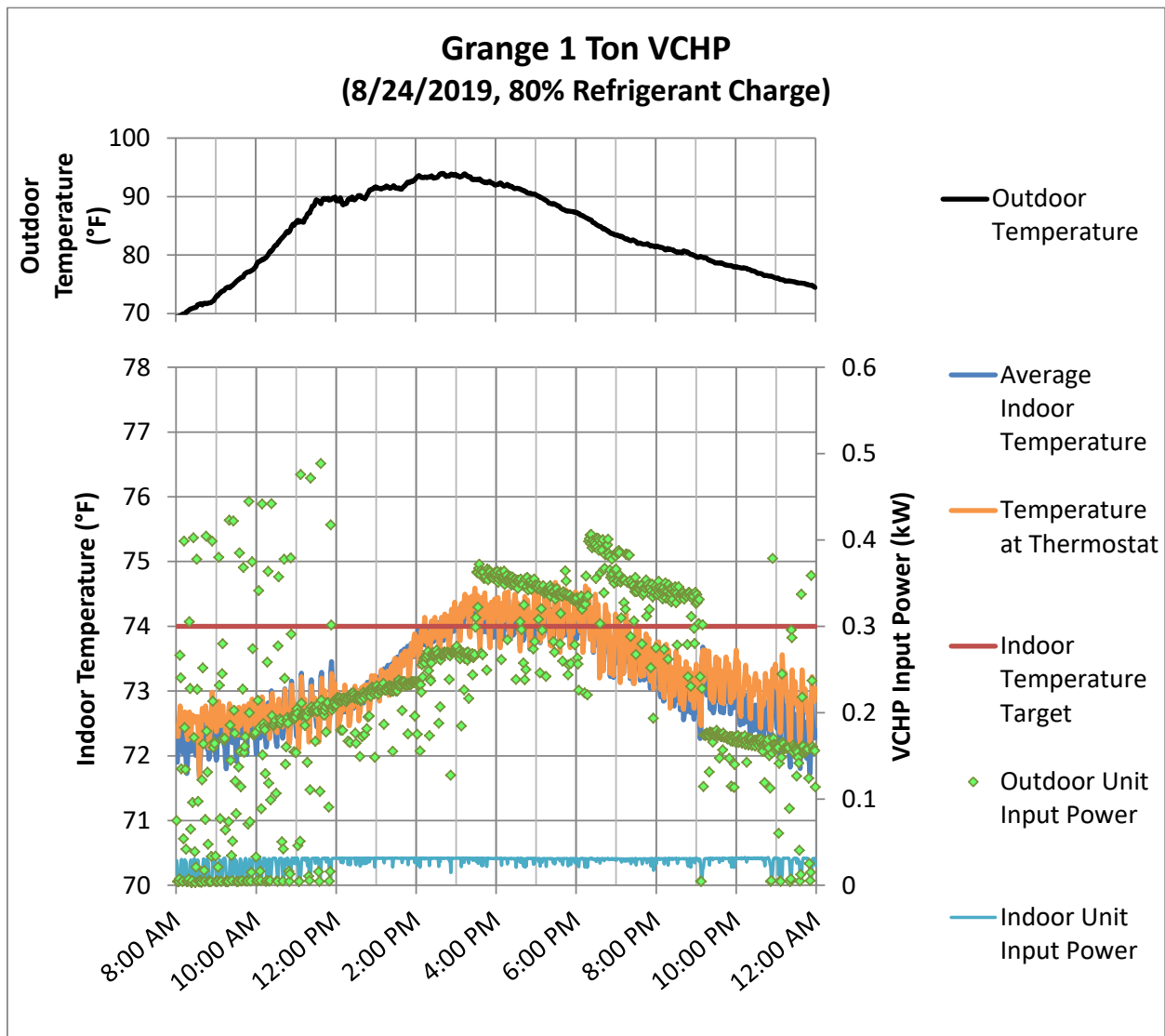


FIGURE 93. GRANGE 1 TON VCHP COOLING EXAMPLE, 80% REFRIGERANT CHARGE

Figure 94 plots the 1 ton VCHP input power against outdoor temperature at each of the four refrigerant levels. The plotted data includes all days the 1 ton VCHP system operated during the 2019 cooling season, and each plotted point represents one minute. The large cluster of data points at about 0.2 kW reflects the system's preferred low speed, while clusters at higher input power levels reflect increased speed/capacity levels. Figure 94 shows that this system operated at higher speeds more frequently at lower refrigerant levels, while at correct refrigerant charge it was able to remain at low speed the majority of the time.

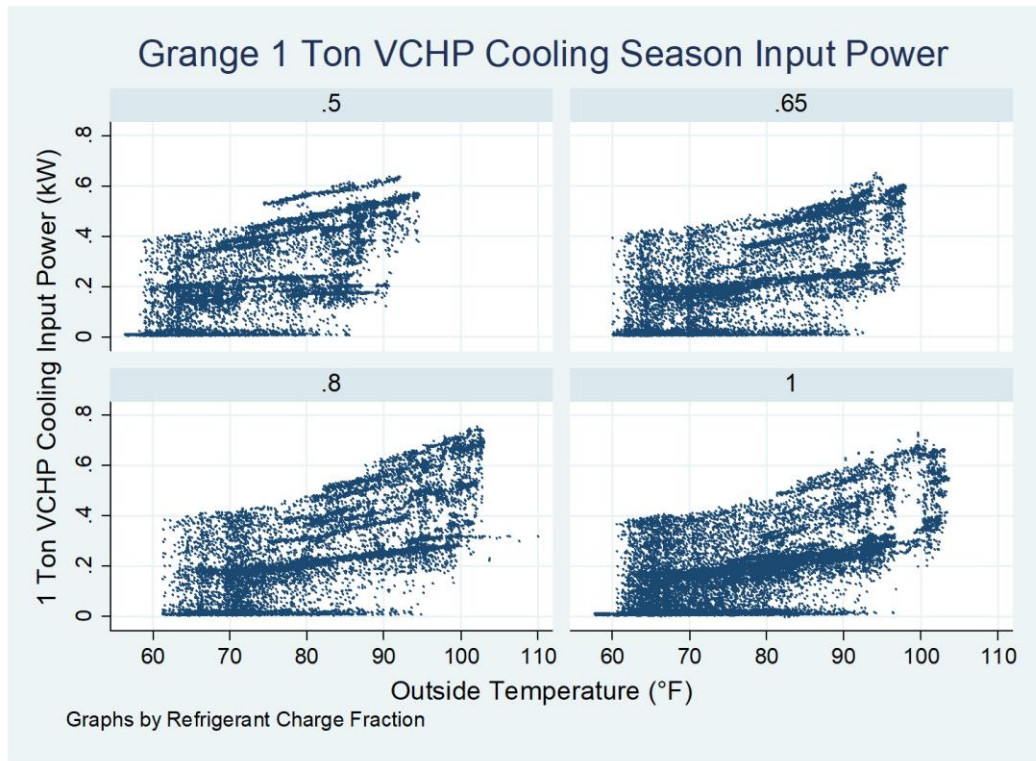


FIGURE 94. GRANGE 1 TON VCHP INPUT POWER IN COOLING MODE

Cycling characteristics for the 1 ton VCHP at each refrigerant level are tabulated against daily average outdoor temperature in Table 42. This system typically runs a large number of short cycles, exceeding 100 cycles per day on mild days. Low refrigerant charge increased the average cycle length and decreased the number of cycles per day.

TABLE 42. GRANGE 1 TON VCHP CYCLING CHARACTERISTICS IN COOLING MODE

	DAILY AVERAGE OUTDOOR TEMPERATURE (°F)	REFRIGERANT LEVEL			
		50%	65%	80%	100%
Average Cycle Length (Minutes)	70	17.9	9.1	-	7.0
	75	22.6	12.2	10.9	10.1
	80	24.2	15.0	14.3	12.5
	85	-	-	18.7	37.3
Average Cycles Per Day	70	53.3	99.0	-	109.4
	75	48.2	85.5	92.0	98.7
	80	49.0	77.5	80.0	84.2
	85	-	-	67.0	39.0

DAILY ENERGY USE

The daily cooling energy use regression results for the 1 ton VCHP are shown in Table 43. Figure 95 displays the monitored and regression predicted daily energy use for each refrigerant level. Figure 96 displays the monitored and regression predicted VCHP daily energy use plotted against daily average outdoor temperature, comparing the modeled results to directly monitored data.

TABLE 43. GRANGE 1 TON VCHP DAILY COOLING ENERGY USE REGRESSION

SYSTEM	VARIABLE	COEFFICIENT	t	95% CONFIDENCE INTERVAL	
1 Ton VCHP	E _{Ref}	0.5393	17.62	0.4772	0.6014
	E _{Ref_R50}	0.4201	11.29	0.3447	0.4956
	E _{Ref_R65}	0.0842	3.13	0.0297	0.1387
	E _{Ref_R80}	0.0932	3.76	0.0429	0.1435
	Constant	0.9056	4.81	0.5236	1.2876
	R ²	0.94			
	Daily Standby kWh	0.25			

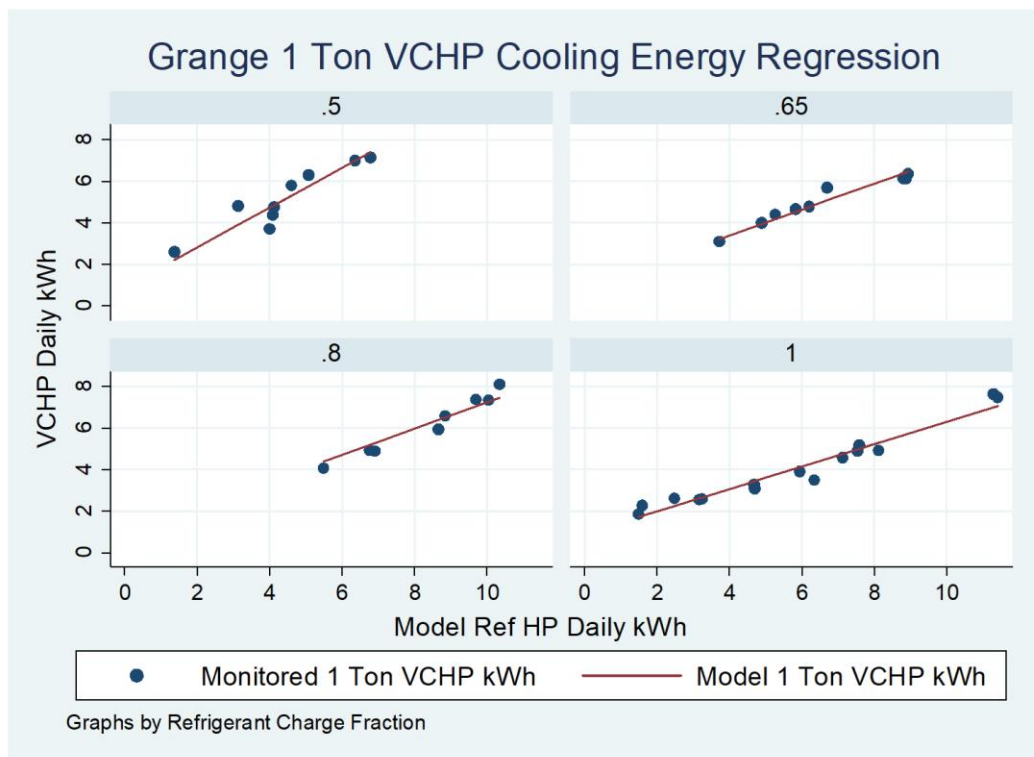


FIGURE 95. GRANGE 1 TON VCHP DAILY COOLING ENERGY REGRESSION

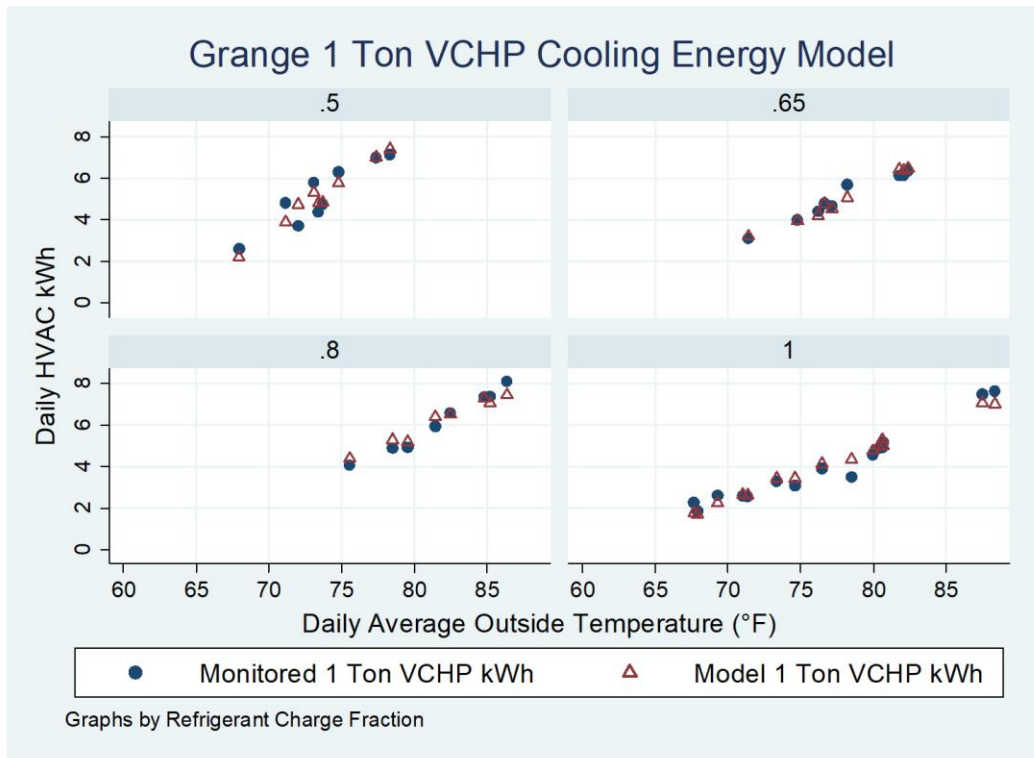


FIGURE 96. GRANGE 1 TON VCHP MONITORED AND MODEL PREDICTED DAILY COOLING ENERGY

The regression predicted normalized seasonal energy use estimates are shown in Table 44. The daily energy use analysis shows efficiency reductions at all three refrigerant undercharge levels, with a loss of 34% at 50% refrigerant charge.

TABLE 44. GRANGE 1 TON VCHP NORMALIZED COOLING SEASON ENERGY USE

SYSTEM	REFRIGERANT LEVEL	SEASONAL ENERGY USE (kWh)	SEASONAL ENERGY USE RELATIVE TO CORRECT REFRIGERANT CHARGE	IMPLIED EFFICIENCY RELATIVE TO CORRECT REFRIGERANT CHARGE
1 Ton VCHP	50%	708.2	152%	66%
	65%	514.4	110%	91%
	80%	519.6	112%	90%
	100%	465.8	100%	100%

AFTERNOON AND EVENING DEMAND

Refrigerant undercharge had a large effect on afternoon and evening demand of the 1 ton VCHP. Because the VCHP needed to operate at higher compressor speeds to meet the cooling load on hot afternoons when undercharged, demand during hot afternoon hours increased by as much as 100%. The average hourly demand relative to performance at correct refrigerant charge is tabulated in Table 45. The monitored energy use during each hour for each refrigerant level is plotted in Figure 97.

Evening demand was more impacted by low refrigerant charge than daily energy use in part because of differences in how indoor temperature was controlled throughout the day. With correct refrigerant charge, indoor temperatures were maintained below target later into the afternoon, effectively shifting some of the evening load to the morning and early afternoon hours. With low refrigerant charge, indoor temperatures exceeded target earlier in the day, resulting in higher loads in the afternoon and evening. This behavior is illustrated in Figure 90 and Figure 91. With correct refrigerant charge indoor temperatures were maintained below target until 4 PM. With 50% refrigerant charge indoor temperatures exceeded target at 11:30 AM and the system had to operate at higher compressor speeds to meet cooling loads in the afternoon and evening.

TABLE 45. GRANGE 1 TON VCHP AVERAGE HOURLY DEMAND RELATIVE TO PERFORMANCE AT CORRECT REFRIGERANT CHARGE

REFRIGERANT LEVEL	HOUR	HOURLY AVERAGE OUTDOOR TEMPERATURE (°F)				
		80	85	90	95	100
50%	2-3 PM	90%	159%	200%	192%	-
	3-4 PM	98%	172%	200%	179%	-
	4-5 PM	145%	180%	163%	131%	-
	5-6 PM	214%	180%	134%	-	-
	6-7 PM	198%	163%	143%	-	-
	7-8 PM	224%	144%	-	-	-
	8-9 PM	159%	-	-	-	-
	9-10 PM	-	-	-	-	-
65%	2-3 PM	-	106%	113%	163%	-
	3-4 PM	-	96%	169%	145%	-
	4-5 PM	100%	-	146%	133%	-
	5-6 PM	-	170%	118%	95%	-
	6-7 PM	150%	122%	120%	-	-
	7-8 PM	154%	117%	-	-	-
	8-9 PM	115%	217%	-	-	-
	9-10 PM	127%	-	-	-	-
80%	2-3 PM	-	-	99%	129%	91%
	3-4 PM	-	-	104%	147%	101%
	4-5 PM	-	-	105%	124%	107%
	5-6 PM	-	-	98%	96%	104%
	6-7 PM	-	124%	126%	-	104%
	7-8 PM	162%	120%	-	109%	-
	8-9 PM	116%	192%	99%	-	-
	9-10 PM	110%	-	-	-	-

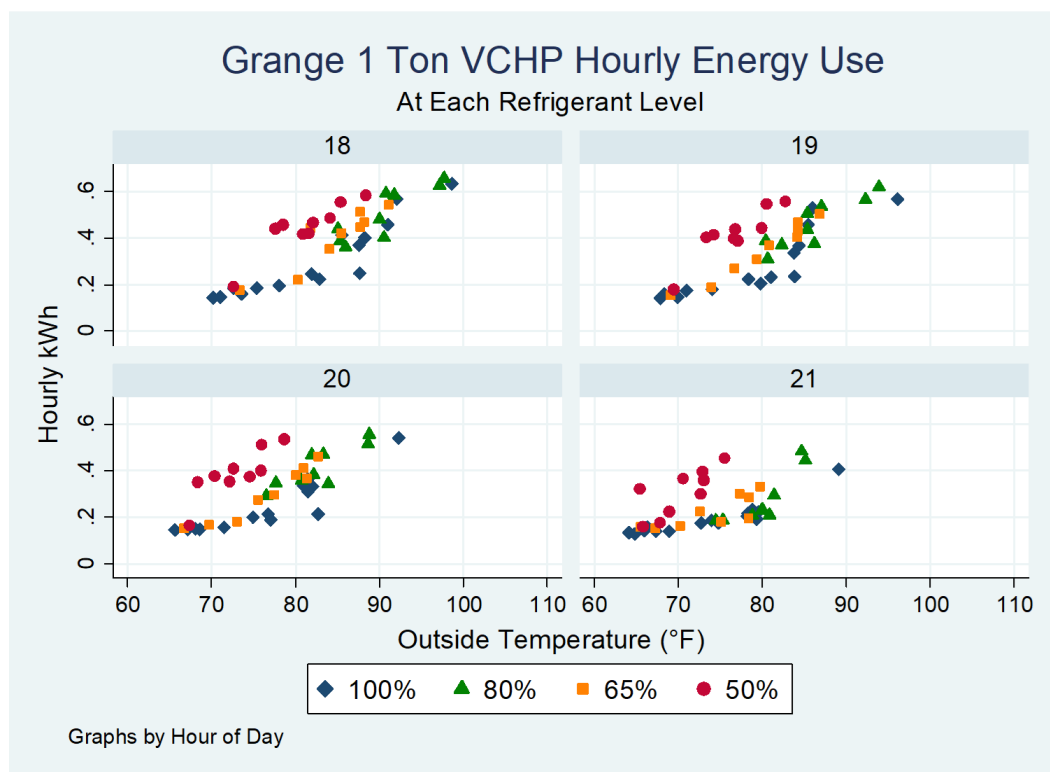
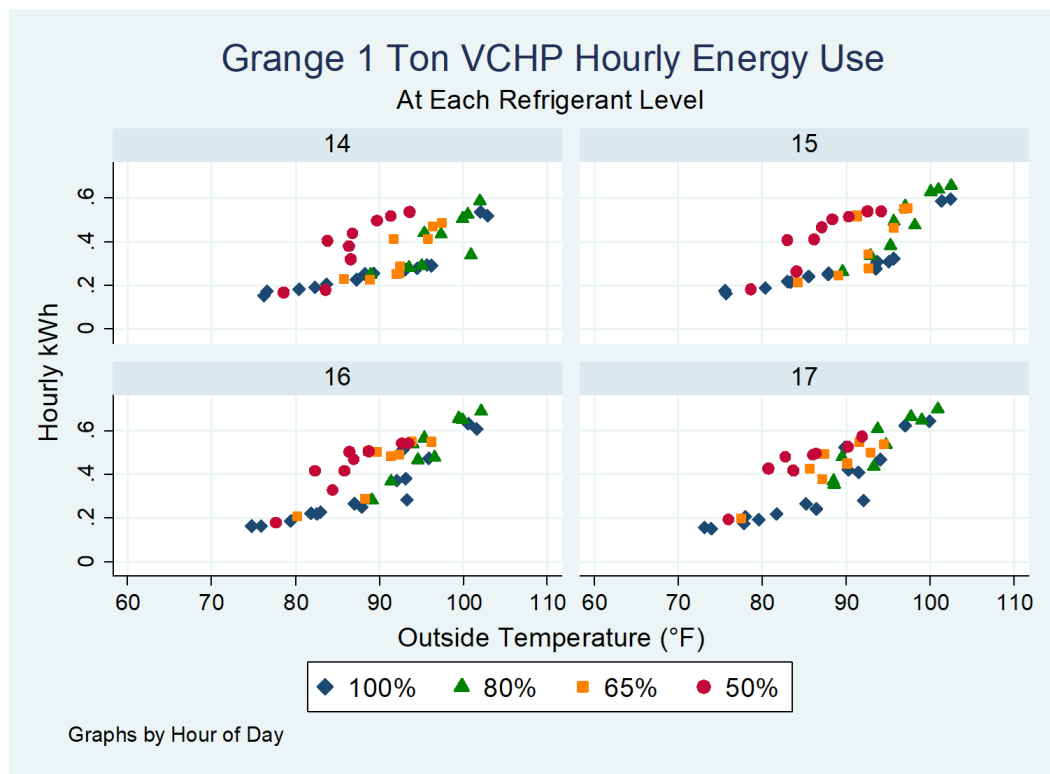


FIGURE 97. GRANGE 1 TON VCHP COOLING SEASON HOURLY ENERGY USE AT EACH REFRIGERANT LEVEL

HEATING SEASON

The 1 ton VCHP system maintained similar indoor temperatures within 1 °F at all refrigerant levels. Average temperatures of each room relative to the target temperature are shown in Figure 98. Average indoor temperatures relative to the temperatures at correct refrigerant charge are shown in Figure 99. The plotted values represent the average of all minutes that occurred during hours with compressor operation during the hour, indicating that the system was providing heating to the house during the hour. This system is controlled by a single thermostat located in the kitchen.

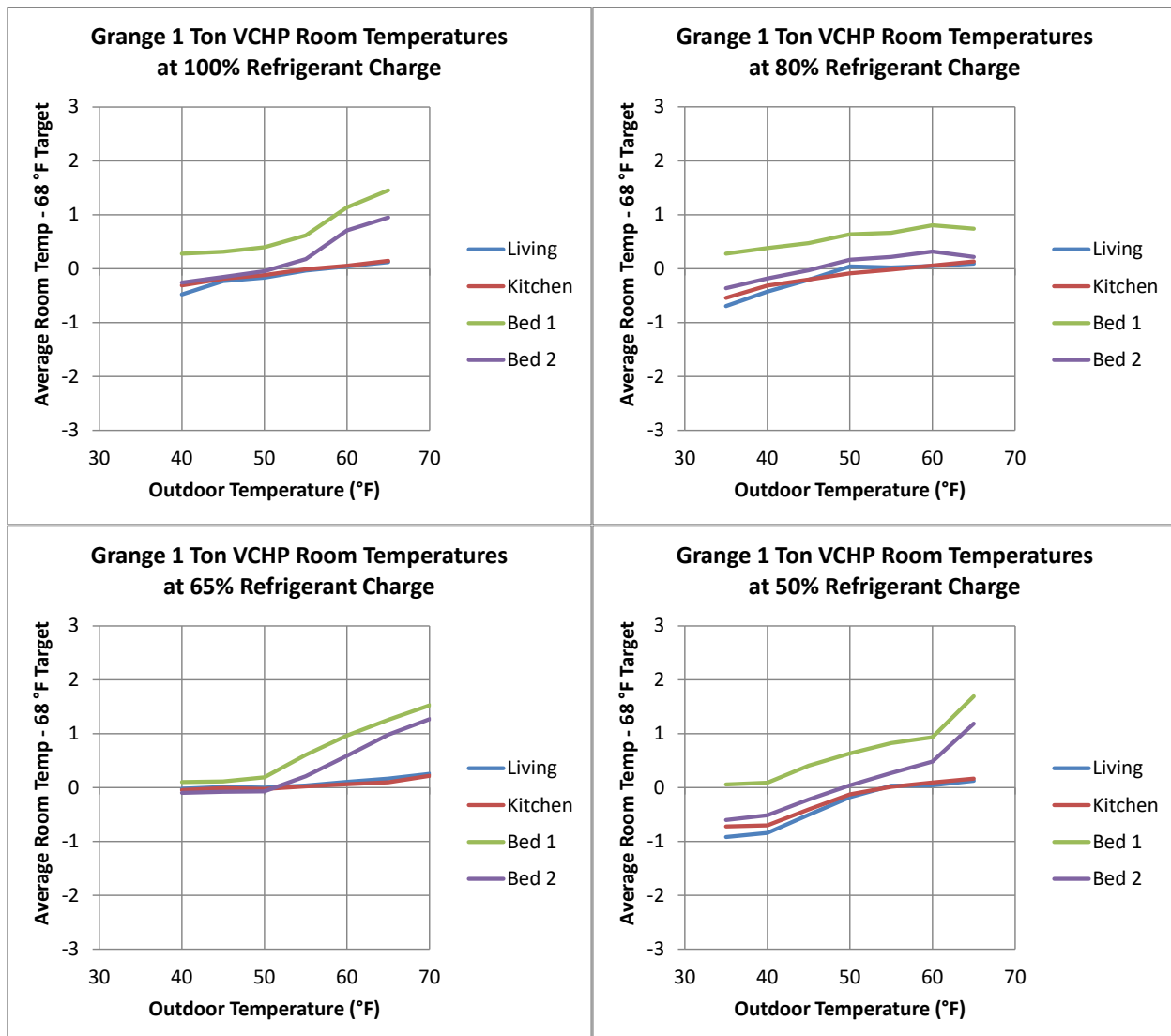


FIGURE 98. GRANGE 1 TON VCHP HEATING SEASON INDOOR TEMPERATURE DELTA TO TARGET

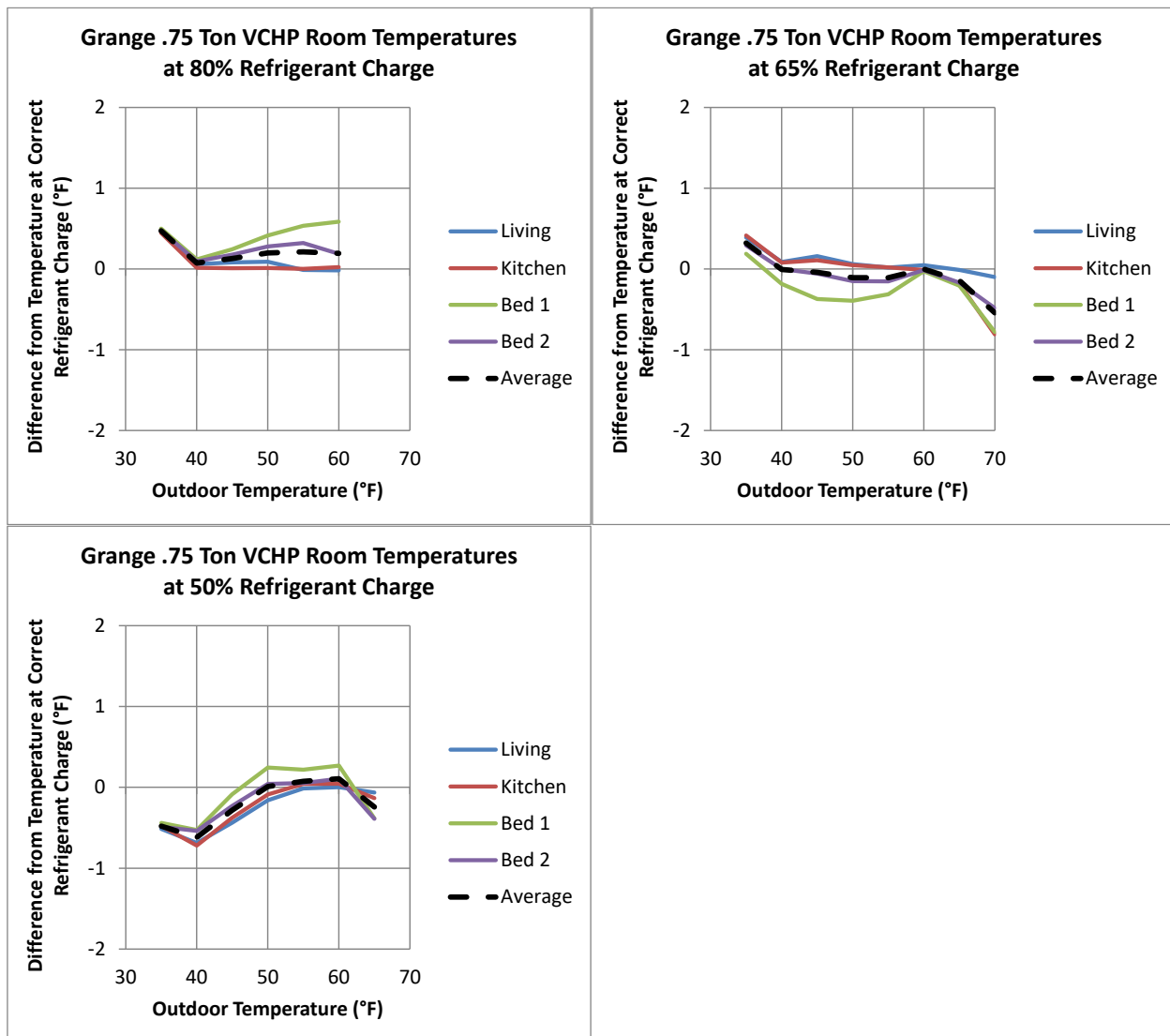


FIGURE 99. GRANGE 1 TON VCHP HEATING SEASON INDOOR TEMPERATURES AT REFRIGERANT UNDERCHARGE CONDITIONS RELATIVE TO TEMPERATURES AT CORRECT REFRIGERANT CHARGE

Figure 100 and Figure 101 show examples of how this system operated on days with similar outdoor temperature at correct refrigerant charge and at 50% refrigerant charge. Each plotted point represents one minute.

The system cycled on the day with correct refrigerant charge and operated continuously on the day with 50% refrigerant charge.

No defrost cycles occurred on either of these days. Defrost operation was infrequent, with only 8 defrost cycles observed during the winter. There was no observed relationship between refrigerant levels and defrost.

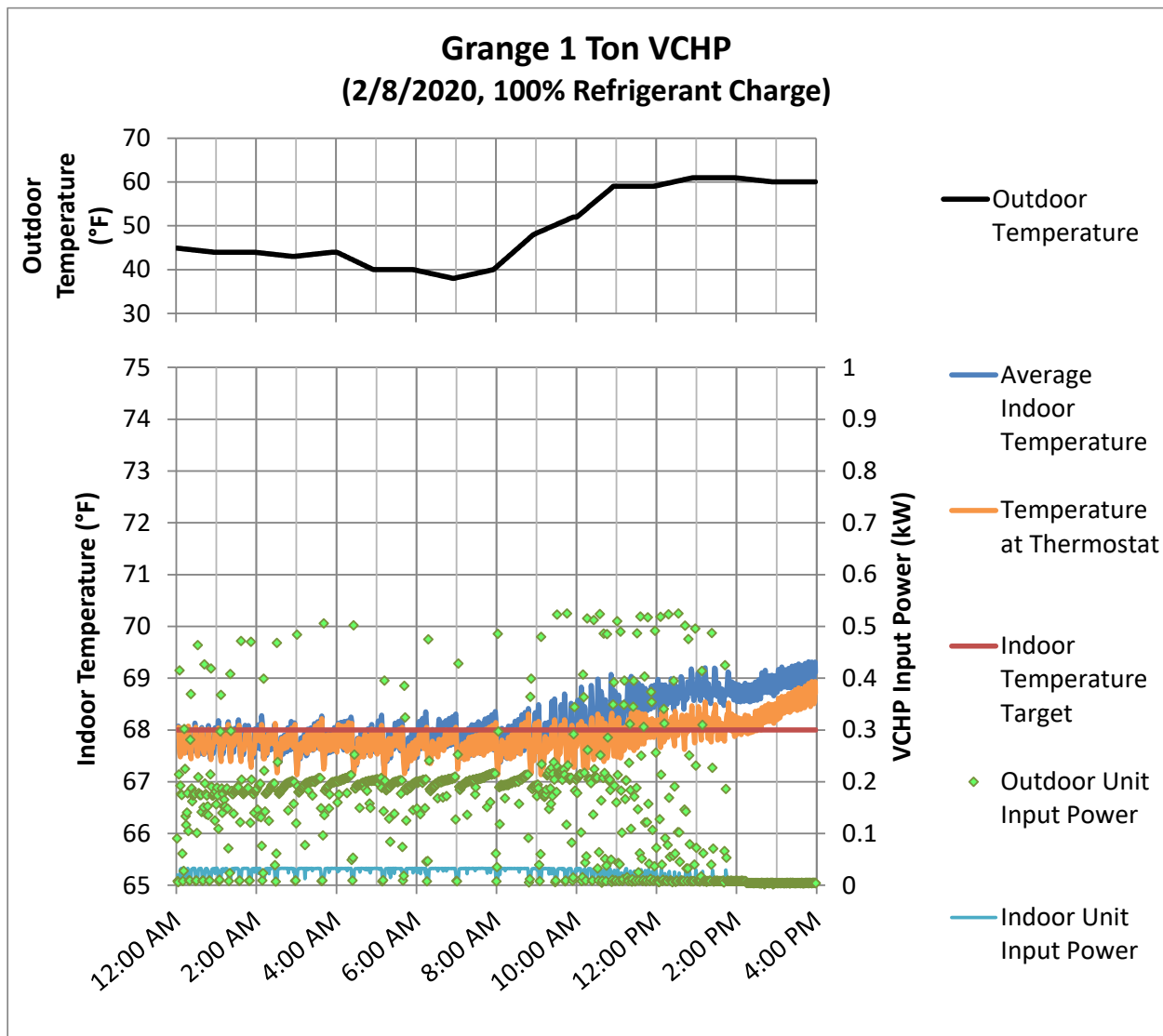


FIGURE 100. GRANGE 1 TON VCHP HEATING EXAMPLE, CORRECT REFRIGERANT CHARGE

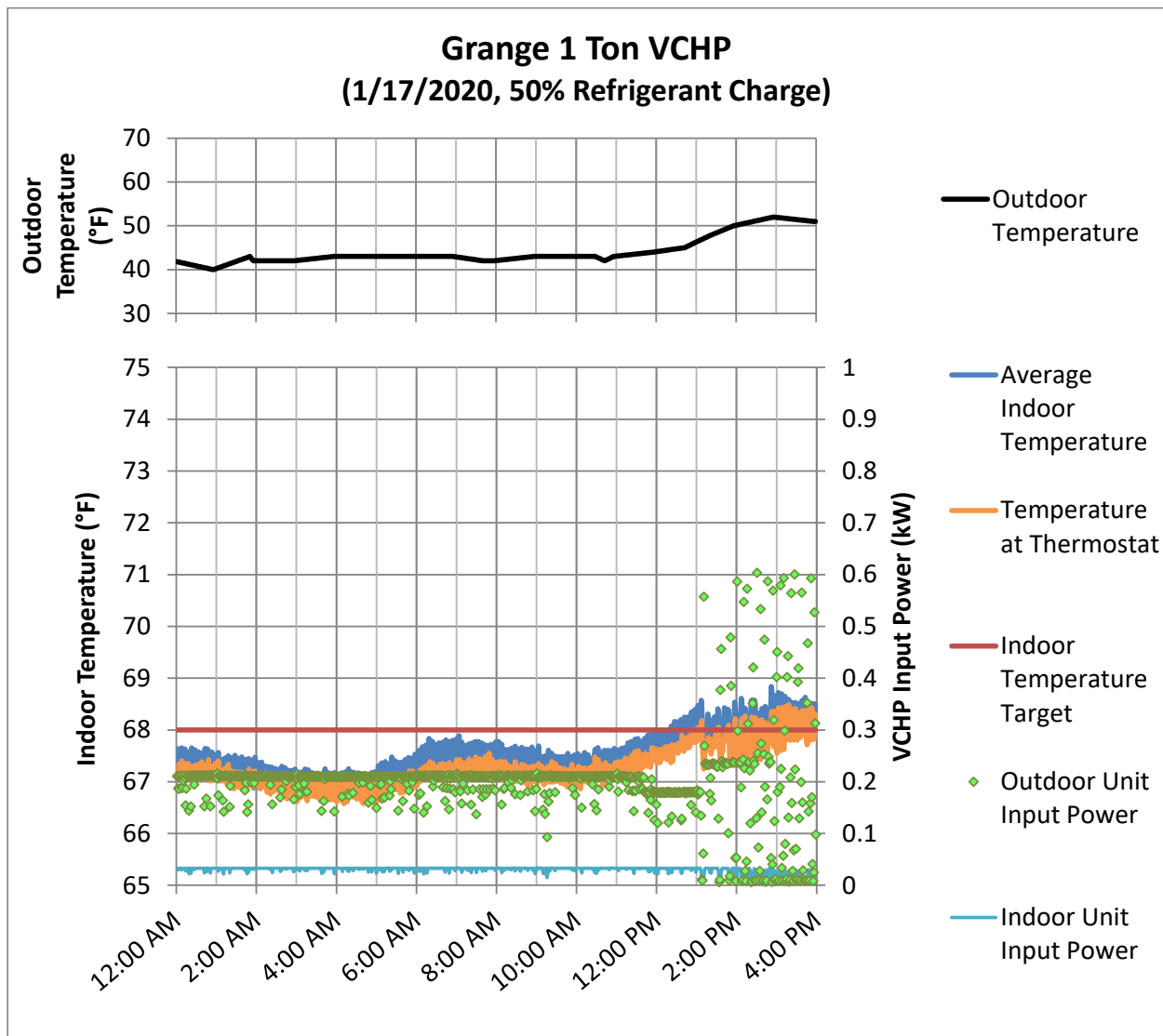


FIGURE 101. GRANGE 1 TON VCHP HEATING EXAMPLE, 50% REFRIGERANT CHARGE

Figure 102 and Figure 103 show days at 65% and 80% refrigerant charge. The 65% day is warmer due to mild weather throughout the 65% testing period.

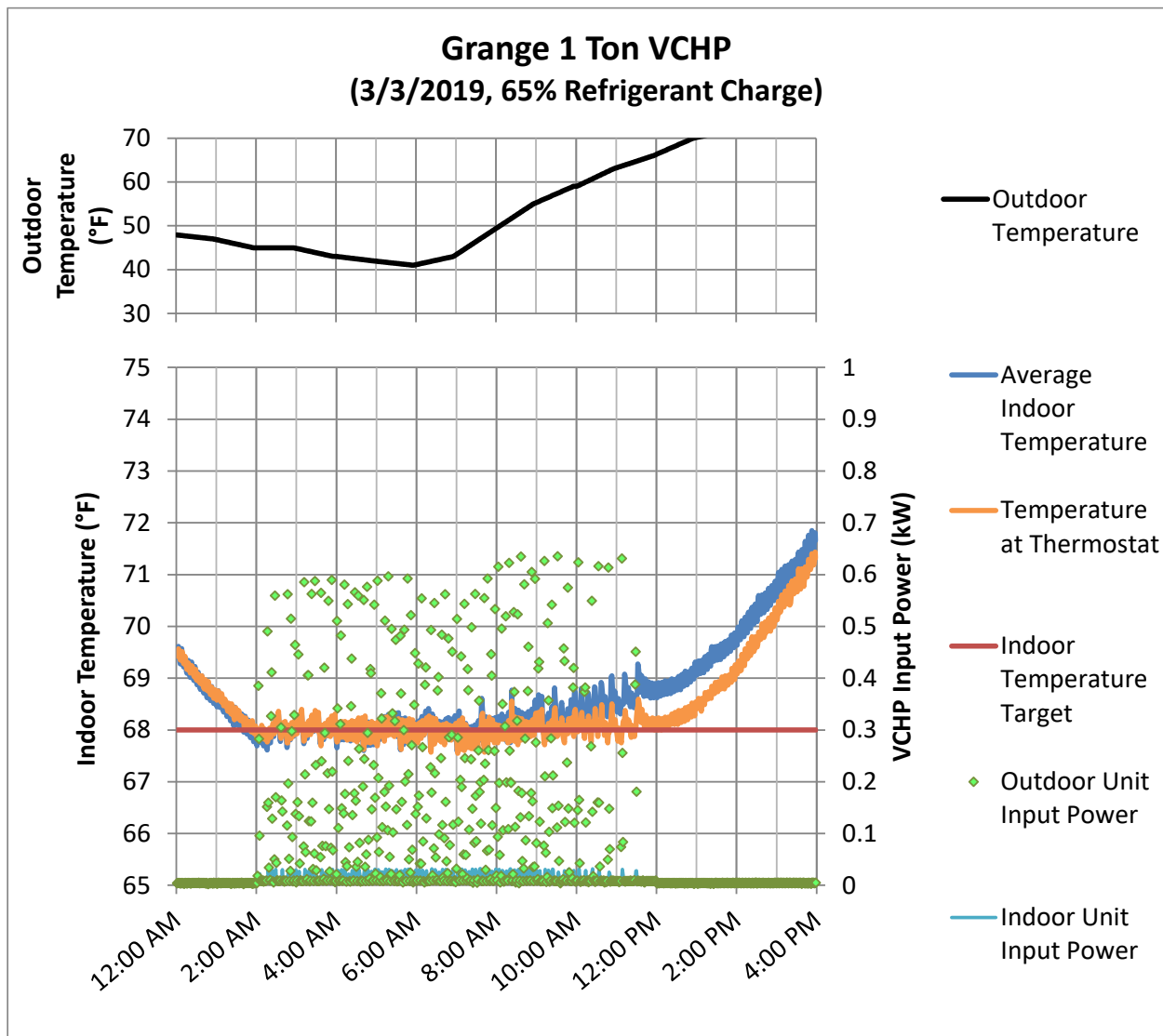


FIGURE 102. GRANGE 1 TON VCHP HEATING EXAMPLE, 65% REFRIGERANT CHARGE

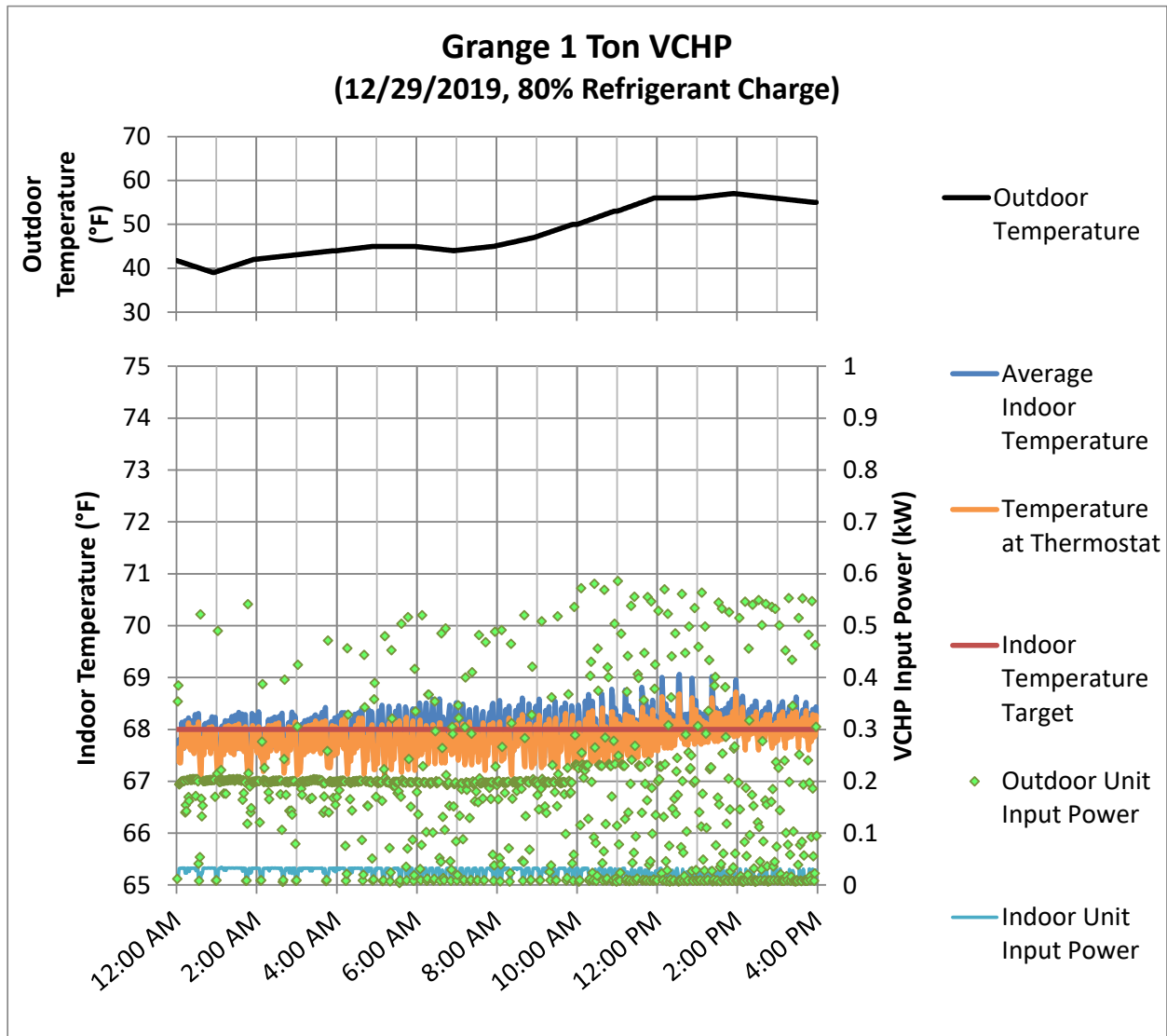


FIGURE 103. GRANGE 1 TON VCHP HEATING EXAMPLE, 80% REFRIGERANT CHARGE

Figure 104 plots the 1 ton VCHP input power against outdoor temperature at each of the four refrigerant levels. The plotted data includes all days the 1 ton VCHP system operated during the 2019-2020 heating season, and each plotted point represents one minute. The large cluster of data points at about 0.2 kW reflects the system's preferred low speed.

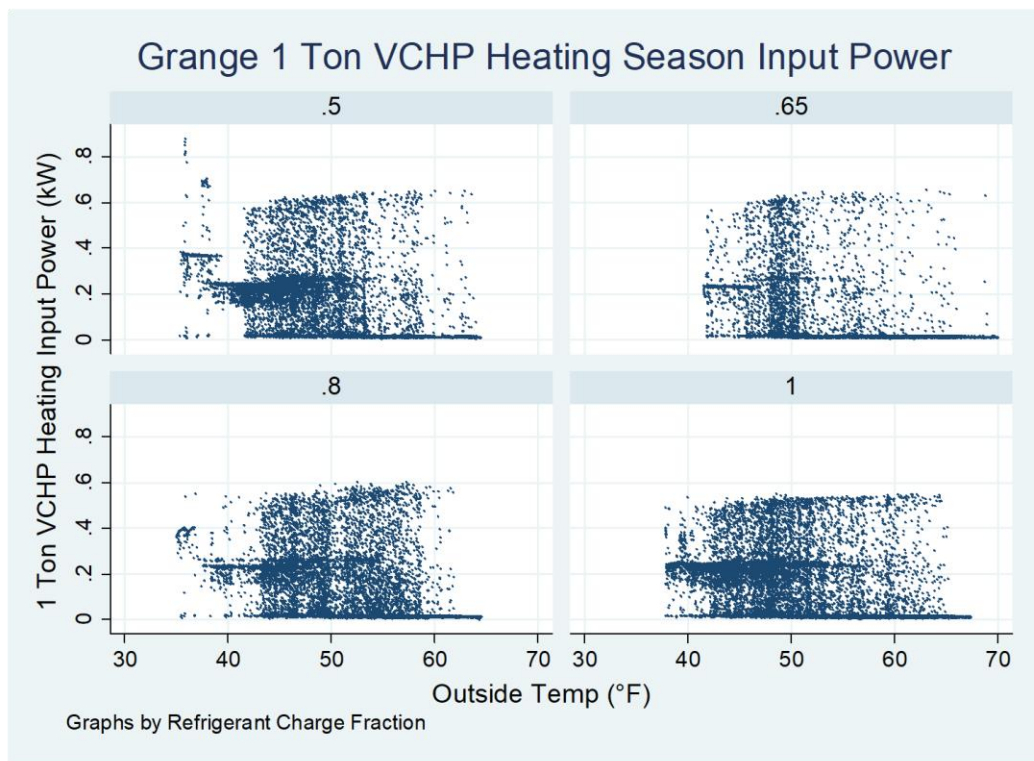


FIGURE 104. GRANGE 1 TON VCHP INPUT POWER IN HEATING MODE

Cycling characteristics for the 1 ton VCHP at each refrigerant level are tabulated against daily average outdoor temperature in Table 46. This system typically runs a large number of short cycles, often exceeding 100 cycles per day. There is no clear relationship between refrigerant levels and cycling behavior.

TABLE 46. GRANGE 1 TON VCHP CYCLING CHARACTERISTICS IN HEATING MODE

	DAILY AVERAGE OUTDOOR TEMPERATURE (°F)	REFRIGERANT LEVEL			
		50%	65%	80%	100%
Average Cycle Length (Minutes)	45	15.5	-	8.8	7.3
	50	7.0	5.2	4.3	7.4
	55	4.4	3.2	2.7	4.6
	60	-	2.8	2.9	3.2
Average Cycles Per Day	45	78.4	-	100.5	147.0
	50	128.7	107.5	162.2	96.1
	55	92.0	88.0	101.0	118.5
	60	-	33.0	55.0	53.0

DAILY ENERGY USE

The daily heating energy use regression results for the 1 ton VCHP are shown in Table 47. Figure 105 displays the monitored and regression predicted daily energy use for each refrigerant level. Figure 106 displays the monitored and regression predicted VCHP daily energy use plotted against daily average outdoor temperature, comparing the modeled results to directly monitored data.

TABLE 47. GRANGE 1 TON VCHP DAILY HEATING ENERGY REGRESSION

SYSTEM	VARIABLE	COEFFICIENT	t	95% CONFIDENCE INTERVAL	
1 Ton VCHP	E _{Ref}	0.1732	13.59	0.1474	0.1989
	E _{Ref_R50}	0.0255	2.57	0.0055	0.0456
	E _{Ref_R65}	-0.0375	-2.21	-0.0718	-0.0032
	E _{Ref_R80}	0.0099	0.89	-0.0126	0.0324
	Constant	0.6177	4.09	0.3125	0.9229
	R ²	0.91			
	Daily Standby kWh	0.35			

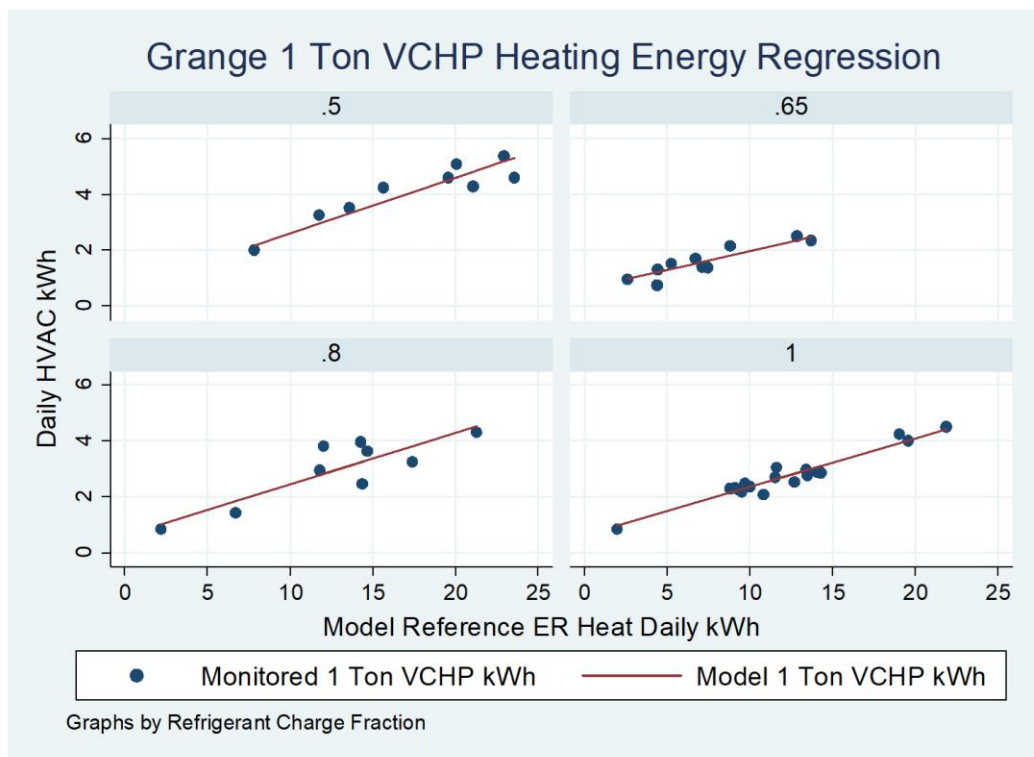


FIGURE 105. GRANGE 1 TON VCHP DAILY HEATING ENERGY REGRESSION

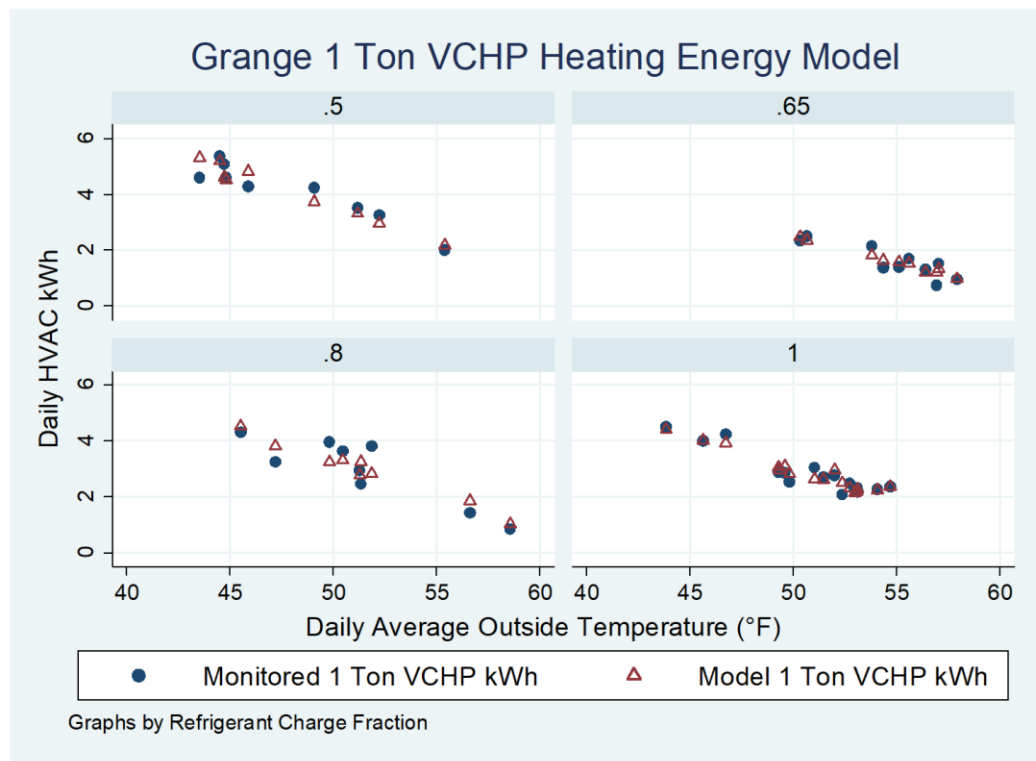


FIGURE 106. GRANGE 1 TON VCHP MONITORED AND MODEL PREDICTED DAILY HEATING ENERGY

The regression predicted normalized seasonal energy use estimates are shown in Table 48. The daily energy use analysis shows an efficiency reduction at 50% refrigerant charge but little or no loss at lower undercharge levels. The 65% monitoring period was limited by warmer weather and low heating loads. The apparent efficiency gain may not be representative of performance at higher heating loads.

TABLE 48. GRANGE 1 TON VCHP NORMALIZED HEATING SEASON ENERGY USE

SYSTEM	REFRIGERANT LEVEL	SEASONAL ENERGY USE (kWh)	SEASONAL ENERGY USE RELATIVE TO CORRECT REFRIGERANT CHARGE	IMPLIED EFFICIENCY RELATIVE TO CORRECT REFRIGERANT CHARGE
1 Ton VCHP	50%	686.0	111%	90%
	65%	524.4	85%	118%
	80%	645.9	104%	96%
	100%	620.6	100%	100%

MAYFAIR HOUSE, REFERENCE SYSTEM

Average temperatures of each room relative to the target temperature are shown in Figure 107 for times when the reference HP system was operating during cooling season, and for times when the electric resistance heaters were operating during heating season. The plotted values represent the average of all minutes that occurred during hours with compressor or resistance heater operation during the hour, indicating that the system was providing cooling or heating to the house during the hour. The reference heat pump system is controlled by a single thermostat located in the living room. The electric resistance heaters in each room are individually controlled by the DAS system based on the monitored temperature in the room. The reference systems maintained average temperatures within 1 °F of target with the exception of the kitchen temperature at mild conditions.

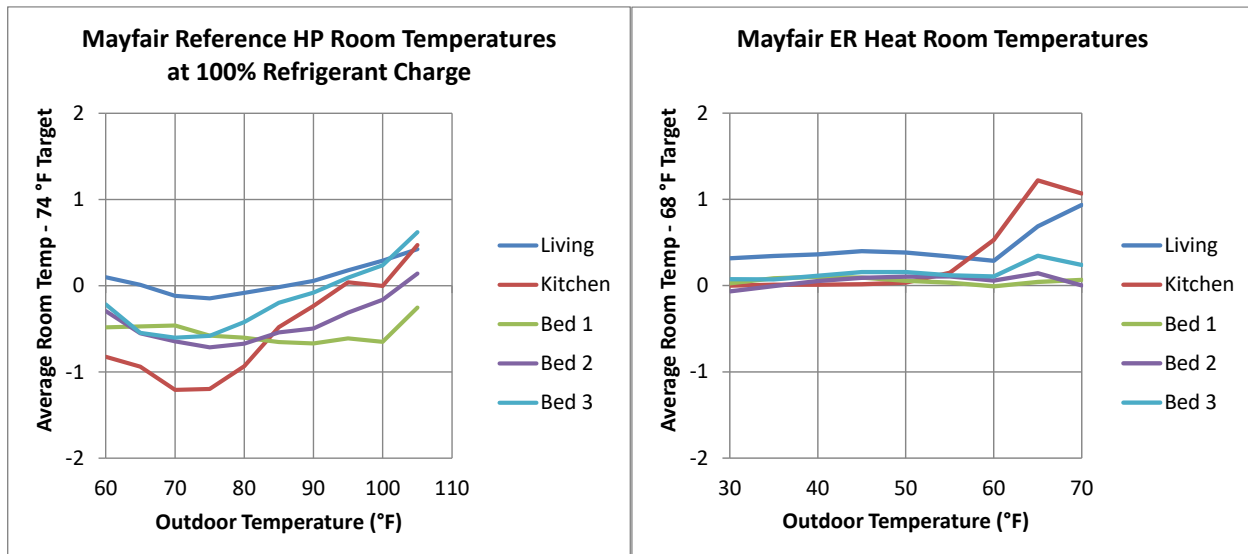


FIGURE 107. MAYFAIR REFERENCE SYSTEM INDOOR TEMPERATURE DELTA TO TARGET

DAILY ENERGY USE

The daily energy use regression results for the reference HP and electric resistance heat are shown in Table 49. Figure 108 displays monitored daily energy use and the regression model for cooling season, and Figure 109 displays the monitored data and the regression model for heating season.

TABLE 49. MAYFAIR REFERENCE SYSTEM DAILY ENERGY USE REGRESSIONS

SEASON	T _{AVG}	T _{HIGH}	T _{LOW}	t _{DAY}	CONST	R ²	DAILY STANDBY KWH
Cooling	0.06695	0.24206	0.22896	-1.40396	-32.32	0.95	0.31
Heating	-1.0069	-0.5846	-0.3132	-9.0672	125.19	0.95	0

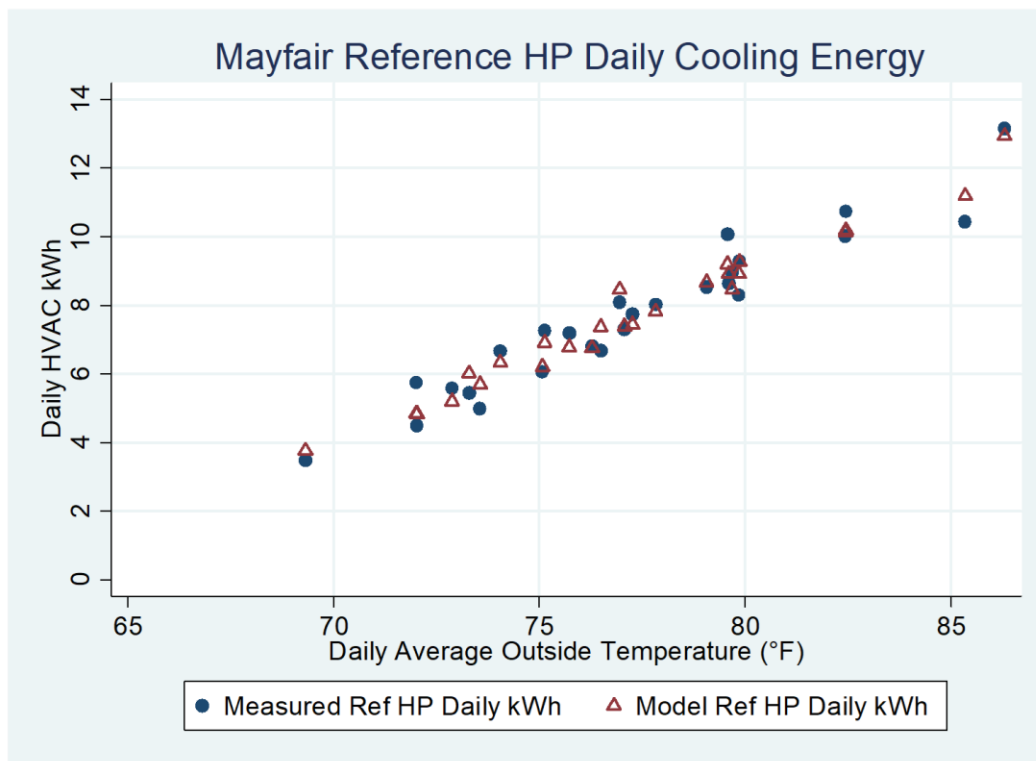


FIGURE 108. MAYFAIR REFERENCE HP DAILY COOLING ENERGY REGRESSION MODEL

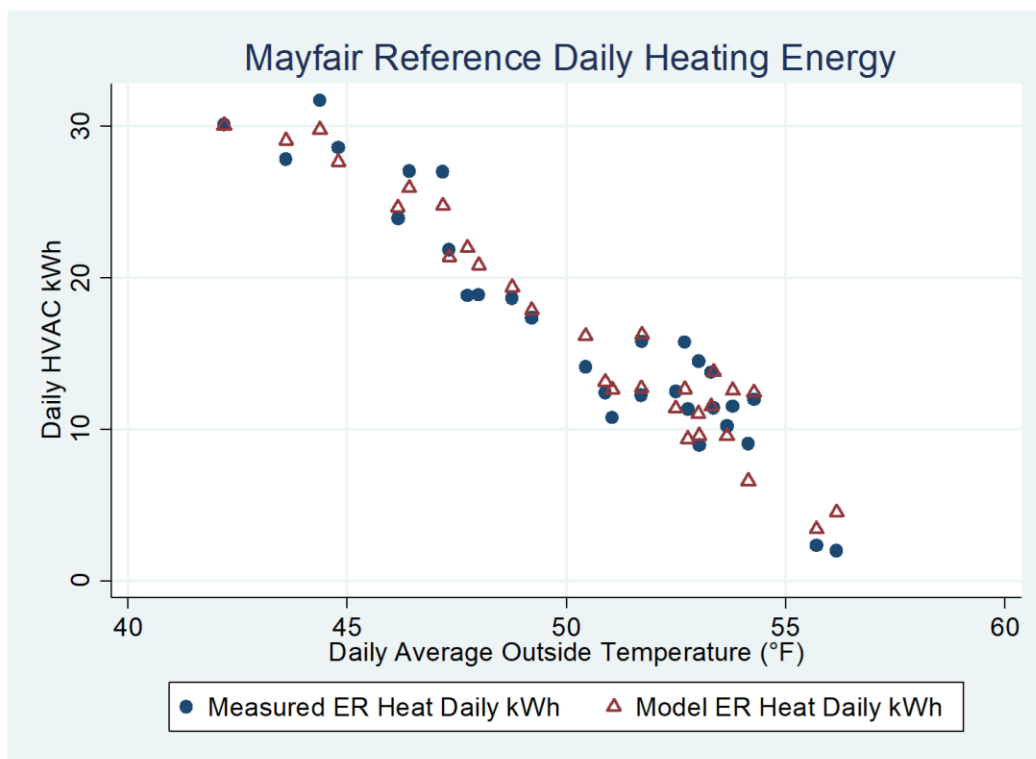


FIGURE 109. MAYFAIR ELECTRIC RESISTANCE HEAT DAILY ENERGY REGRESSION MODEL

MAYFAIR HOUSE, 1.5 TON VCHP

COOLING SEASON

The 1.5 ton VCHP system failed to maintain indoor temperatures at the desired setpoint under hot outdoor conditions at all refrigerant undercharge conditions. Indoor temperatures increased with increasing outdoor temperature, and with increasing levels of refrigerant undercharge.

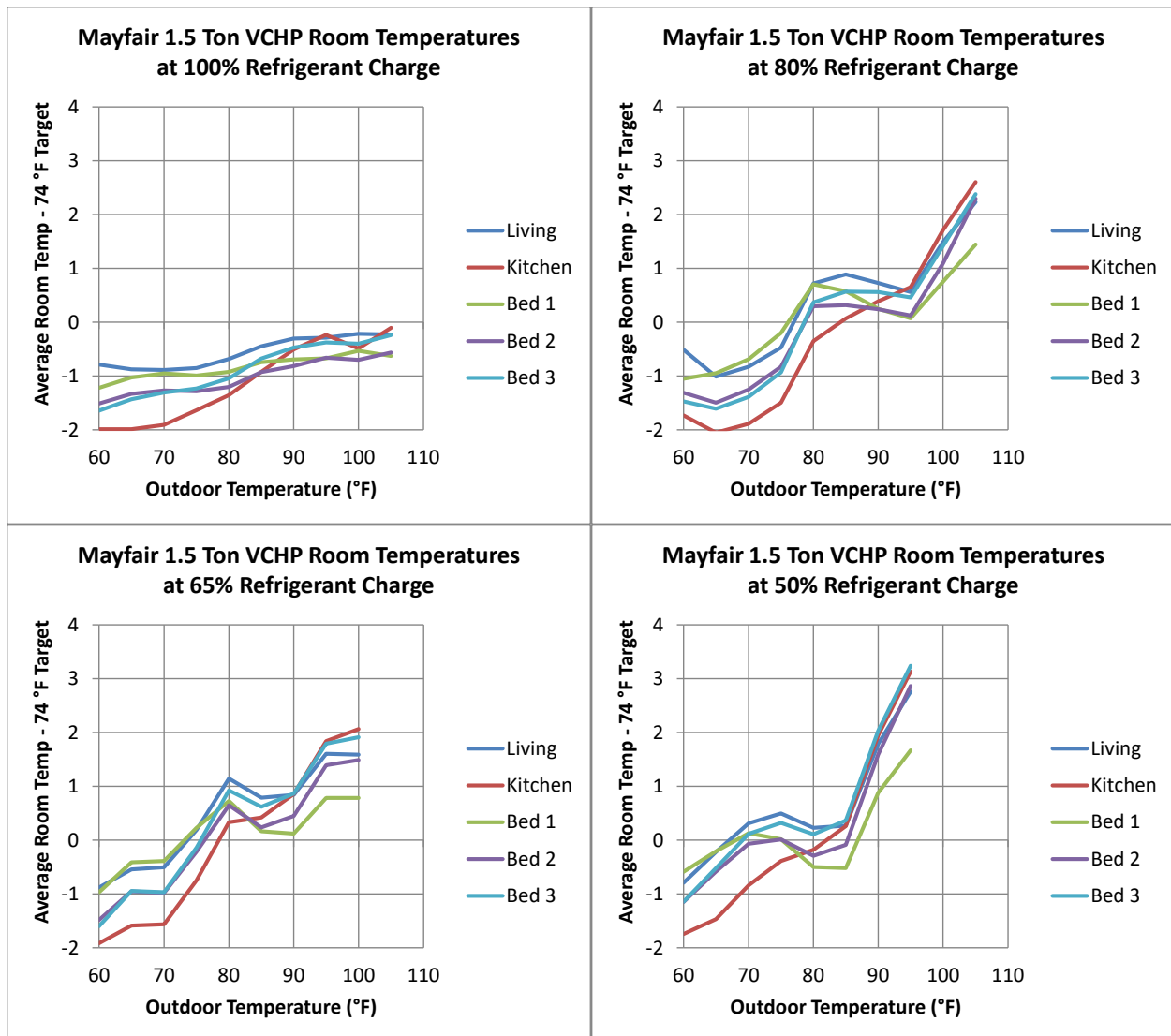


FIGURE 110. MAYFAIR 1.5 TON VCHP COOLING SEASON INDOOR TEMPERATURE DELTA TO TARGET

Average temperatures of each room relative to the target temperature are shown in Figure 110. Average indoor temperatures relative to the temperatures at correct refrigerant charge are shown in Figure 111. The plotted values represent the average

of all minutes that occurred during hours with compressor operation during the hour, indicating that the system was providing cooling to the house during the hour. This system is controlled by a single thermostat located in the living room.

These results show that the system was not meeting cooling loads at the refrigerant undercharge conditions, and that the shortfall in delivered cooling capacity increased with refrigerant undercharge amount and outdoor temperature. This behavior affects both the total amount of cooling energy used by the system and the slope of energy use relative to outdoor temperature and cooling loads.

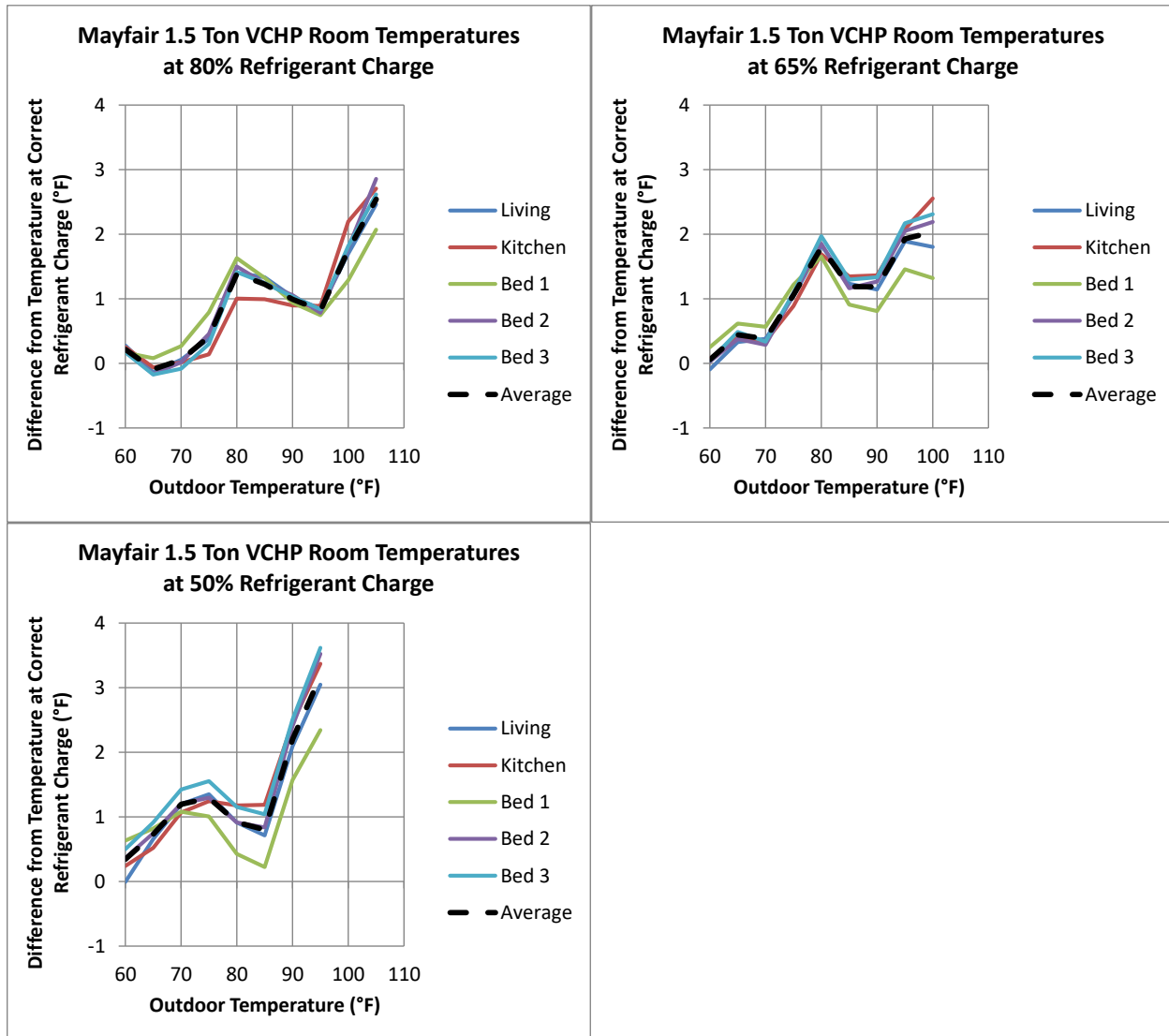


FIGURE 111. MAYFAIR 1.5 TON VCHP COOLING SEASON INDOOR TEMPERATURES AT REFRIGERANT UNDERCHARGE CONDITIONS RELATIVE TO TEMPERATURES AT CORRECT REFRIGERANT CHARGE

The failure to control indoor temperature is not necessarily indicative that the VCHP system was incapable of producing enough cooling capacity to meet loads. In this case it was caused by control programming that failed to modulate capacity to

maintain indoor temperature at the desired setpoint. Indoor temperature was not constant even at 100% refrigerant charge in Figure 110, and indoor temperature variation and operation at reduced capacity levels insufficient to meet the cooling load was also observed during prior years when this system was monitored (Wilcox 2018, Wilcox 2019).

Figure 112 and Figure 113 show examples of how this system operated on days with similar outdoor temperature at correct refrigerant charge and at 50% refrigerant charge. Each plotted point represents one minute.

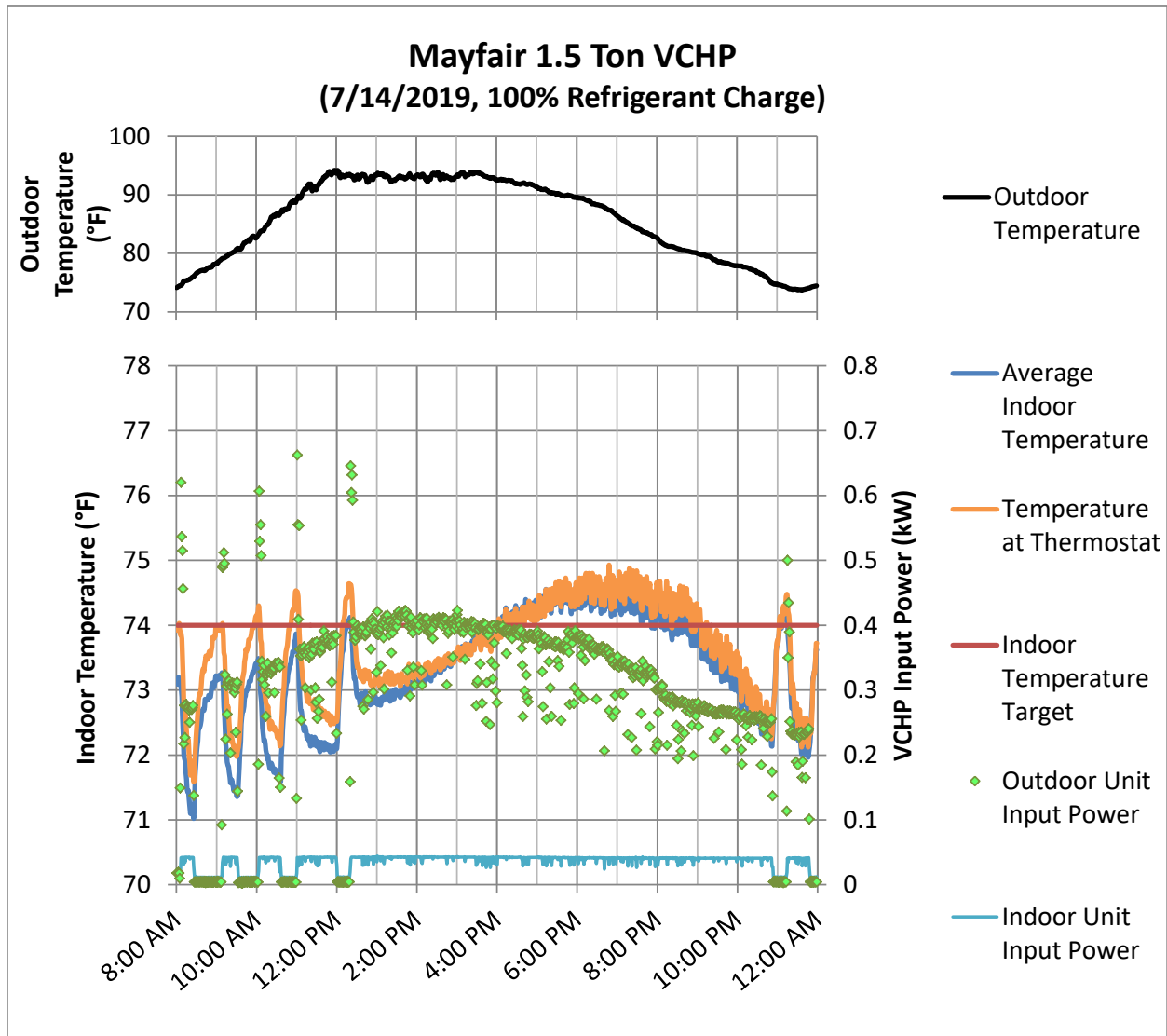


FIGURE 112. MAYFAIR 1.5 TON VCHP COOLING EXAMPLE, CORRECT REFRIGERANT CHARGE

In the morning of both days, when outdoor temperatures were mild and cooling loads were low, the system cycled and maintained indoor temperatures about 1 °F below target. The scattering of higher outdoor unit input power data points during

the morning hours reflects that this system began each cycle with capacity above the minimum level, and then reduced capacity after several minutes. As outdoor temperature warmed and cooling loads increased, the system settled into constant low speed operation. It remained at low speed through the afternoon on both days, even as indoor temperatures climbed above target.

Only when indoor temperature reached 4 °F above target at 7 PM on Figure 113 (50% charge) did compressor speed/capacity increase. Indoor temperature decreased while higher speed operation continued, indicating that the system was producing sufficient capacity to meet the cooling load. At about 8:45 PM input power reverted to the lower level even though indoor temperature had not reached setpoint. This demonstrates that the system is capable of producing more cooling capacity than occurred during testing, and that it would likely be capable of delivering sufficient capacity to meet cooling loads if the control programming modulated capacity in a way that caused the thermostat setpoint to be satisfied.

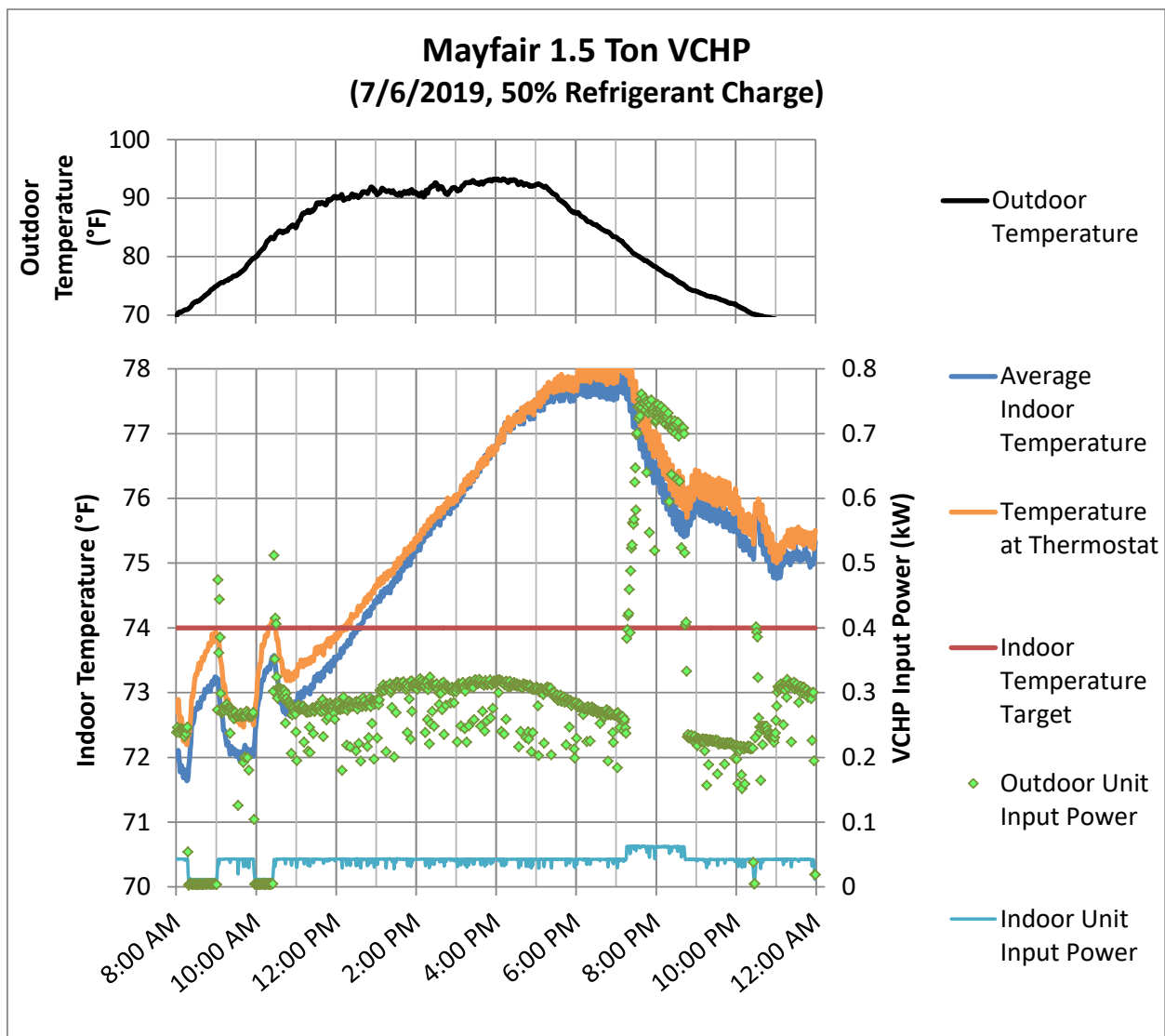


FIGURE 113. MAYFAIR 1.5 TON VCHP COOLING EXAMPLE, 50% REFRIGERANT CHARGE

Figure 114 and Figure 115 show similar days at 65% and 80% refrigerant charge.

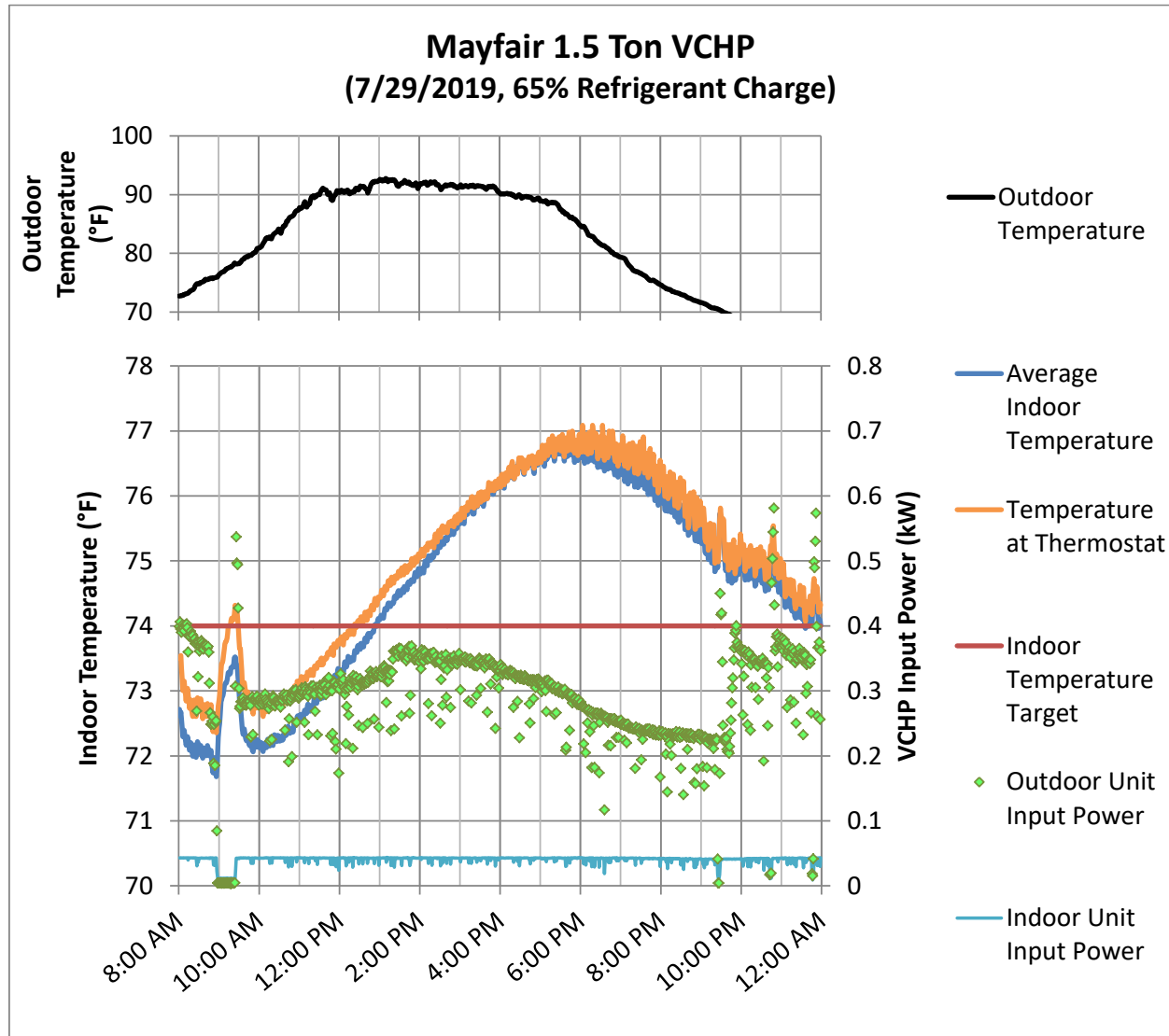


FIGURE 114. MAYFAIR 1.5 TON VCHP COOLING EXAMPLE, 65% REFRIGERANT CHARGE

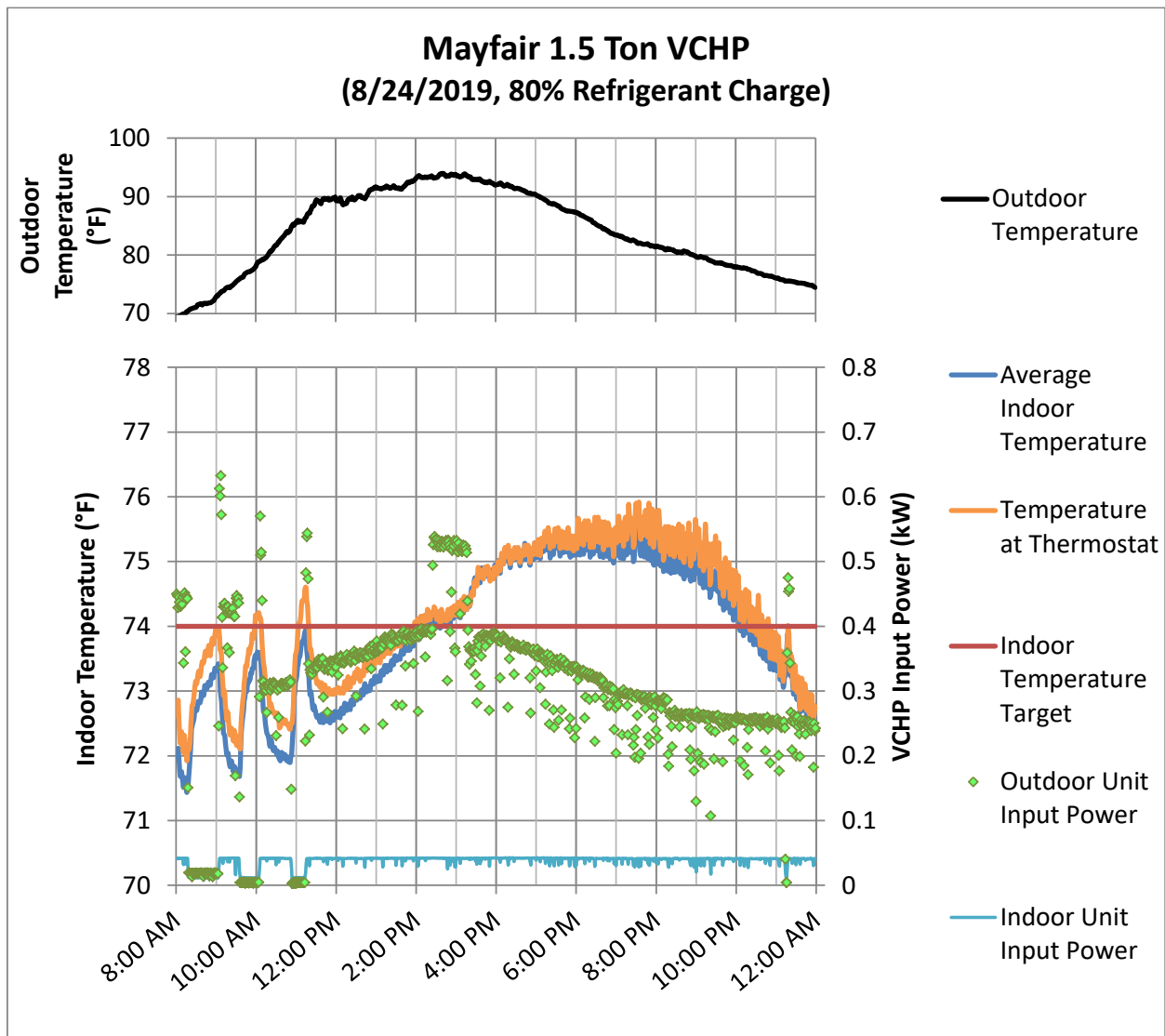


FIGURE 115. MAYFAIR 1.5 TON VCHP COOLING EXAMPLE, 80% REFRIGERANT CHARGE

Figure 116 plots the 1.5 ton VCHP input power against outdoor temperature at each of the four refrigerant levels. The plotted data includes all days the 1.5 ton VCHP system operated during the 2019 cooling season, and each plotted point represents one minute. It is clear from these plots that the system operated at low speed/capacity between 0.2 and 0.4 kW input power the majority of the time and operated at higher speeds infrequently at all four refrigerant levels.

Also of note on Figure 116 (also visible at 11PM on Figure 113 and 10PM on Figure 114) is the increase in input power that occurs below about 75 °F outdoor temperature. The monitored data does not show any increase in capacity at these conditions. The manufacturer of this system has stated that the increased power draw is caused by a low ambient control activating at cooler outdoor temperatures in cooling mode. Technical and operational details of this control were not disclosed and

are not known to the research team, but it has the effect of nearly doubling the average watt draw of the unit when activated.

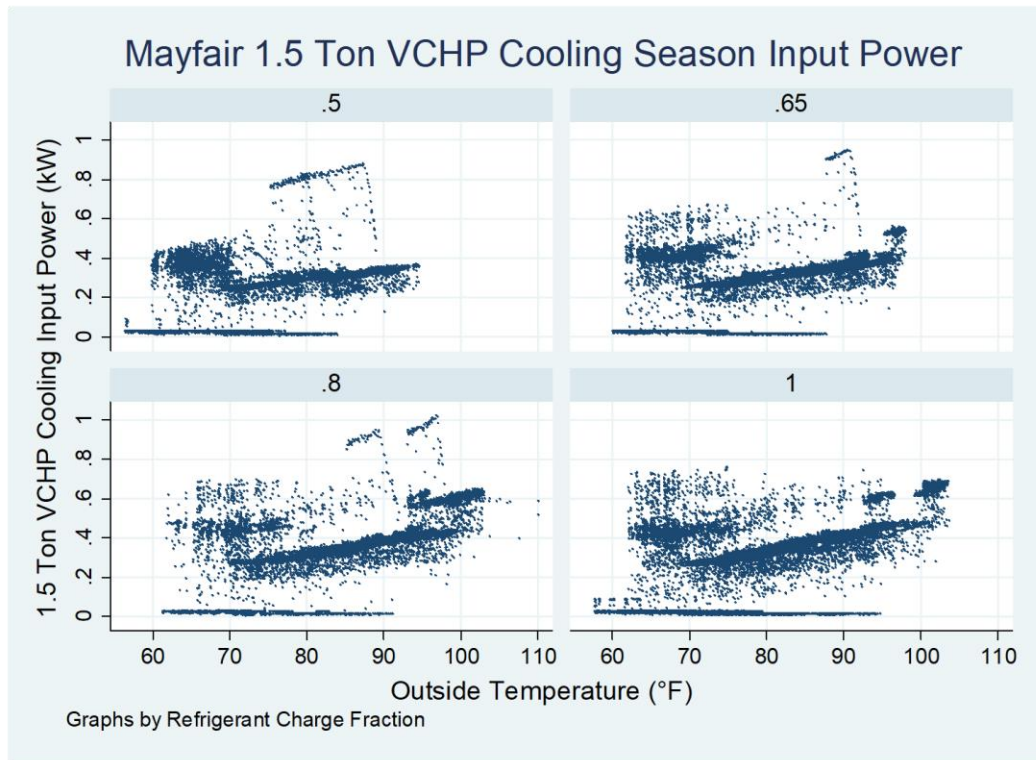


FIGURE 116. MAYFAIR 1.5 TON VCHP INPUT POWER IN COOLING MODE

Cycling characteristics for the 1.5 Ton VCHP at each refrigerant level are tabulated against daily average outdoor temperature in Table 50. Low refrigerant charge increased average cycle length and decreased the number of cycles per day. This system ran long cycles on average, with few cycles per day under all conditions.

TABLE 50. MAYFAIR 1.5 TON VCHP CYCLING CHARACTERISTICS IN COOLING MODE

	DAILY AVERAGE OUTDOOR TEMPERATURE (°F)	REFRIGERANT LEVEL			
		50%	65%	80%	100%
Average Cycle Length (Minutes)	70	144.3	70.4	-	44.6
	75	134.2	103.1	99.5	59.7
	80	135.2	104.1	93.3	74.8
	85	-	-	134.3	132.6
Average Cycles Per Day	70	7.0	15.0	-	13.8
	75	9.0	10.8	9.0	14.0
	80	8.0	11.5	12.0	12.4
	85	-	-	9.3	10.0

DAILY ENERGY USE

The daily cooling energy use regression results for the 1.5 Ton VCHP are shown in Table 51. Figure 117 displays the monitored and regression predicted daily energy use for each refrigerant level. Figure 118 displays the monitored and regression predicted VCHP daily energy use plotted against daily average outdoor temperature, comparing the modeled results to directly monitored data.

The increased scatter in measured VCHP energy use on days with low refrigerant levels is related to uneven indoor temperature control and failure to meet the cooling load throughout the day. The cooling capacity provided by this system on hot afternoons was largely independent of the cooling load in the house. The system operated at the same speed/capacity for most of the afternoon regardless of indoor temperature or cooling load. Some portion of the unmet load from one day then spilled over into the following day. The overall result is energy use that is more scattered and less strongly correlated to cooling loads or outdoor temperature than would have occurred if cooling loads had been met at all times.

TABLE 51. MAYFAIR 1.5 TON VCHP DAILY COOLING ENERGY REGRESSION

SYSTEM	VARIABLE	COEFFICIENT	t	95% CONFIDENCE INTERVAL	
1.5 Ton VCHP	E _{Ref}	0.4988	9.52	0.3925	0.6051
	E _{Ref_R50}	0.2219	4.21	0.1151	0.3287
	E _{Ref_R65}	0.1115	2.86	0.0323	0.1907
	E _{Ref_R80}	0.1038	2.82	0.0291	0.1785
	Constant	1.5101	3.77	0.6982	2.3220
	R ²	0.83			
	Daily Standby kWh	0.38			
	Total Cooling Season Crankcase Heat kWh	17.7			

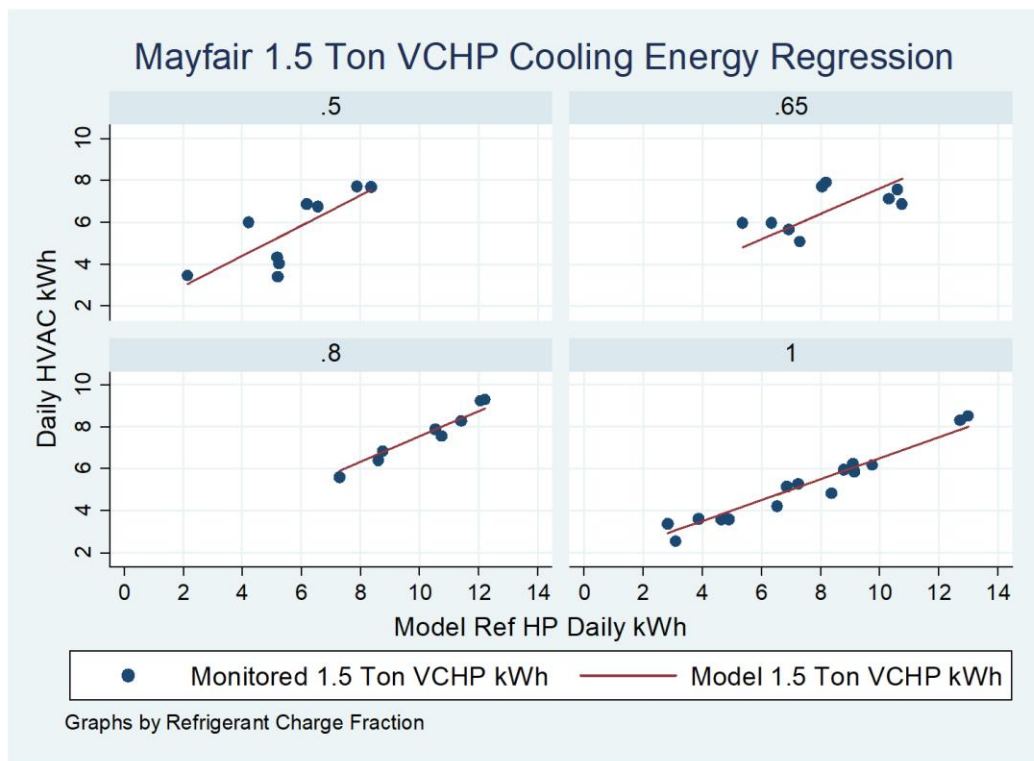


FIGURE 117. MAYFAIR 1.5 TON VCHP DAILY COOLING ENERGY REGRESSION

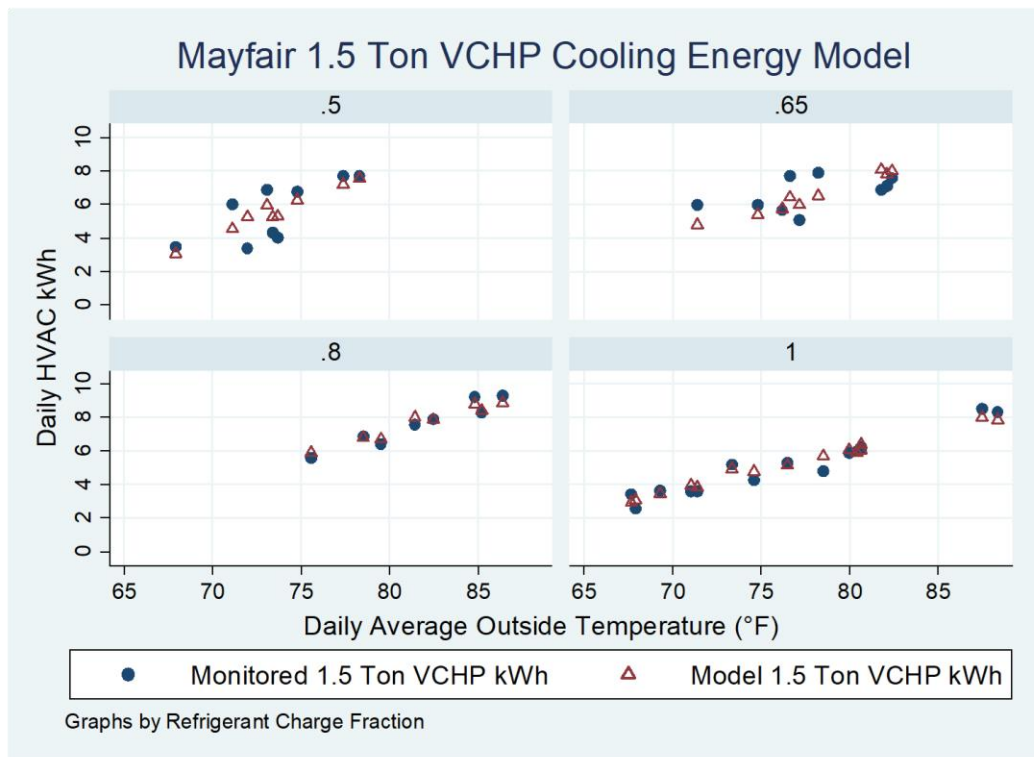


FIGURE 118. MAYFAIR 1.5 TON VCHP MONITORED AND MODEL PREDICTED DAILY COOLING ENERGY

The regression predicted normalized seasonal energy use estimates are shown in Table 52. The daily energy use analysis shows efficiency reductions at all three refrigerant undercharge levels, with a loss of 21% at 50% refrigerant charge. The energy and efficiency impacts of low refrigerant levels on the performance of this system are underestimated due to failure to meet cooling loads. Energy use at low refrigerant levels would have been greater if the system had produced the same amount of cooling at all refrigerant levels.

TABLE 52. MAYFAIR 1.5 TON VCHP NORMALIZED COOLING SEASON ENERGY USE

SYSTEM	REFRIGERANT LEVEL	SEASONAL ENERGY USE (kWh)	SEASONAL ENERGY USE RELATIVE TO CORRECT REFRIGERANT CHARGE	IMPLIED EFFICIENCY RELATIVE TO CORRECT REFRIGERANT CHARGE
1.5 Ton VCHP	50%*	927.2	126%	79%
	65%*	832.4	113%	88%
	80%	825.8	112%	89%
	100%	736.6	100%	100%

* Efficiency impacts of low refrigerant levels are underestimated. The system did not meet cooling loads under these conditions.

AFTERNOON AND EVENING DEMAND

Refrigerant undercharge had relatively little effect on afternoon and evening demand of the 1.5 ton VCHP. Because this system usually did not increase capacity to meet afternoon cooling loads, low refrigerant charge often decreased demand. In some evening hours, when indoor temperatures became so warm that the system did increase compressor speed, demand increased by as much as 127%. Average hourly demand relative to performance at correct refrigerant charge is tabulated in Table 53. The monitored energy use during each hour for each refrigerant level is plotted in Figure 119.

TABLE 53. MAYFAIR 1.5 TON VCHP AVERAGE HOURLY DEMAND RELATIVE TO PERFORMANCE AT CORRECT REFRIGERANT CHARGE

REFRIGERANT LEVEL	HOUR	HOURLY AVERAGE OUTDOOR TEMPERATURE (°F)				
		80	85	90	95	100
50%	2-3 PM	116%	87%	83%	65%	-
	3-4 PM	103%	78%	84%	70%	-
	4-5 PM	89%	85%	80%	80%	-
	5-6 PM	98%	83%	84%	-	-
	6-7 PM	102%	84%	150%	-	-
	7-8 PM	137%	227%	-	-	-
	8-9 PM	135%	-	-	-	-
	9-10 PM	-	-	-	-	-
65%	2-3 PM	-	95%	93%	92%	-
	3-4 PM	-	79%	92%	88%	-
	4-5 PM	92%	-	89%	90%	-
	5-6 PM	-	91%	90%	79%	-
	6-7 PM	105%	88%	108%	-	-
	7-8 PM	89%	97%	-	-	-
	8-9 PM	87%	91%	-	-	-
	9-10 PM	92%	-	-	-	-
80%	2-3 PM	-	-	98%	103%	92%
	3-4 PM	-	-	99%	107%	94%
	4-5 PM	-	-	97%	109%	101%
	5-6 PM	-	-	94%	90%	111%
	6-7 PM	-	94%	112%	-	159%
	7-8 PM	98%	115%	-	206%	-
	8-9 PM	92%	100%	82%	-	-
	9-10 PM	97%	-	-	-	-

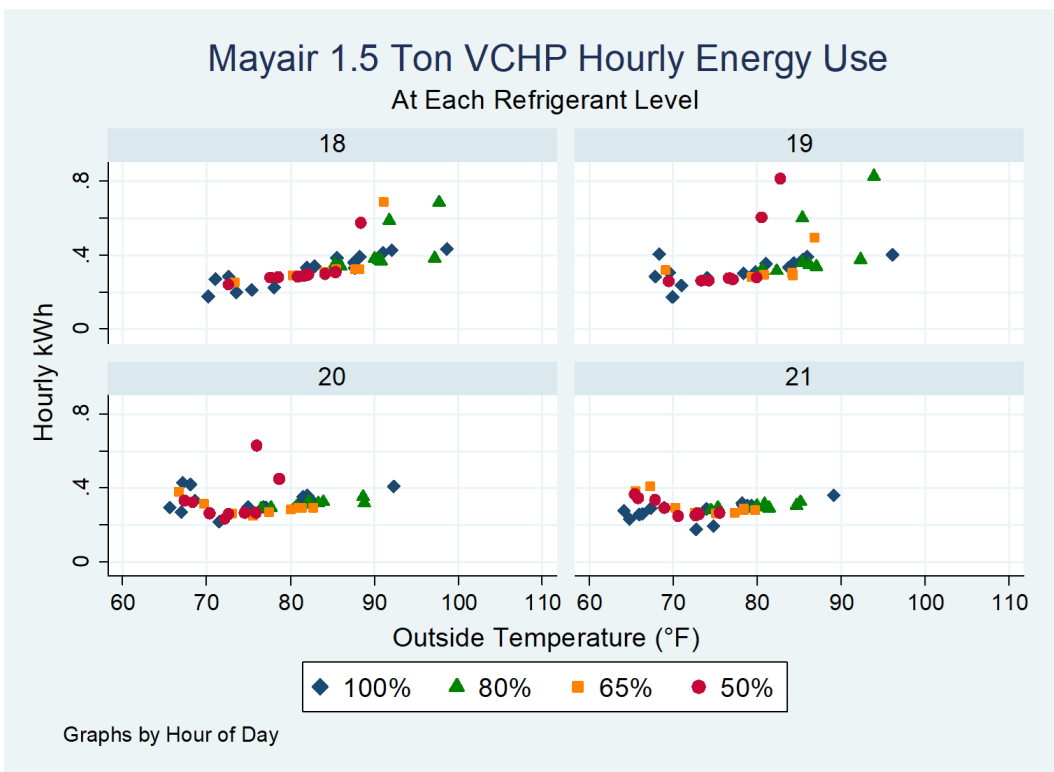
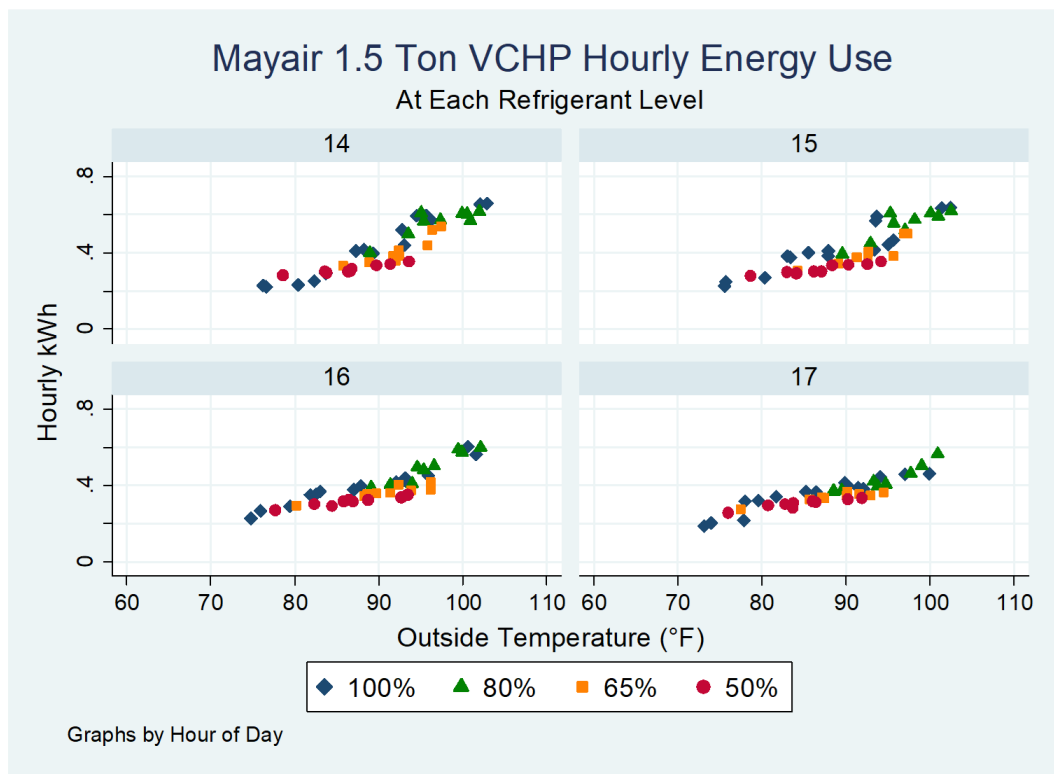


FIGURE 119. MAYFAIR 1.5 TON VCHP COOLING SEASON HOURLY ENERGY USE AT EACH REFRIGERANT LEVEL

HEATING SEASON

The 1.5 Ton VCHP system maintained similar indoor temperatures at all refrigerant levels during heating season. Average temperatures of each room relative to the target temperature are shown in Figure 120. Average indoor temperatures relative to the temperatures at correct refrigerant charge are shown in Figure 121. The plotted values represent the average of all minutes that occurred during hours with compressor operation during the hour, indicating that the system was providing heating to the house during the hour.

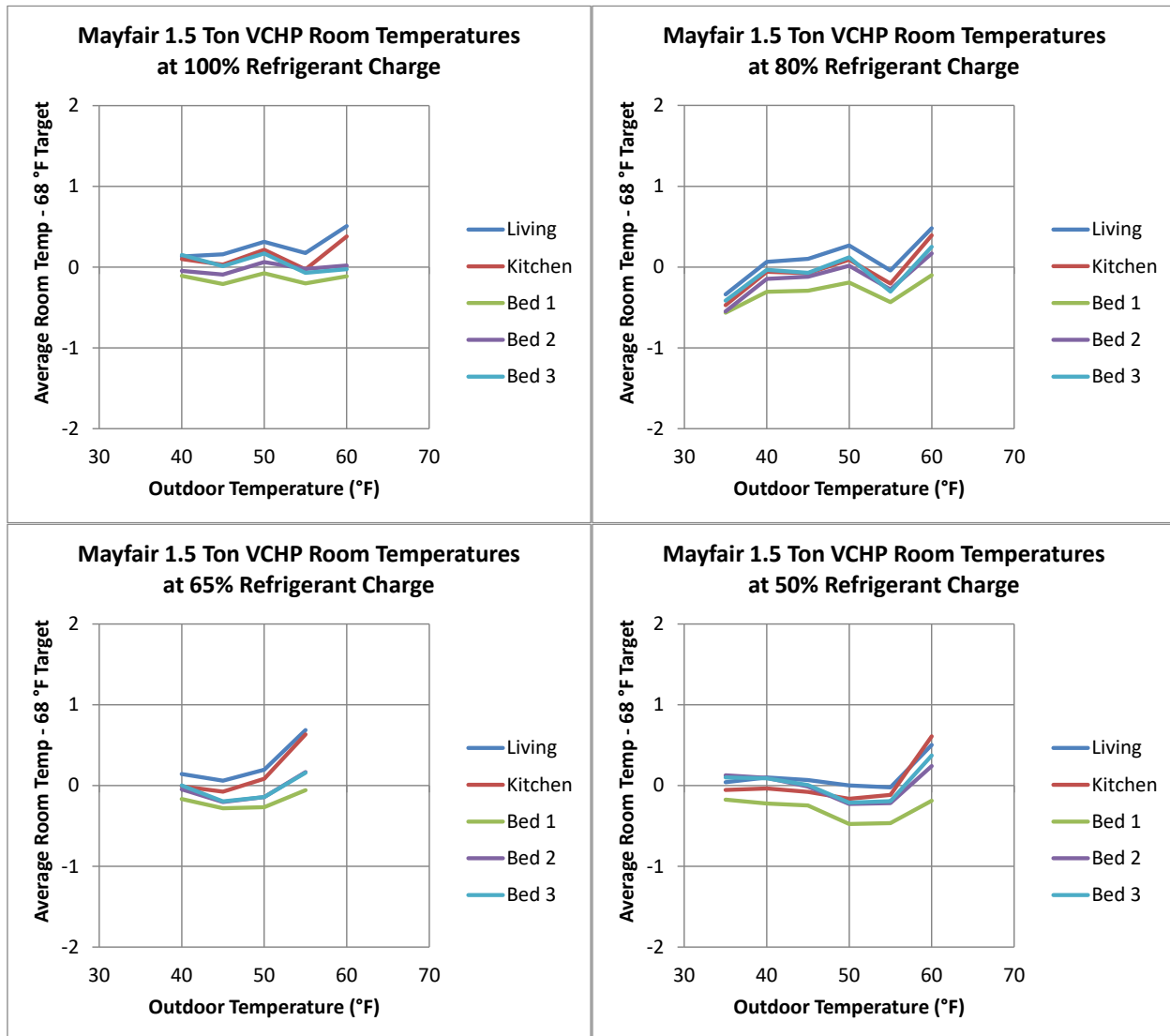


FIGURE 120. MAYFAIR 1.5 TON VCHP HEATING SEASON INDOOR TEMPERATURE DELTA TO TARGET

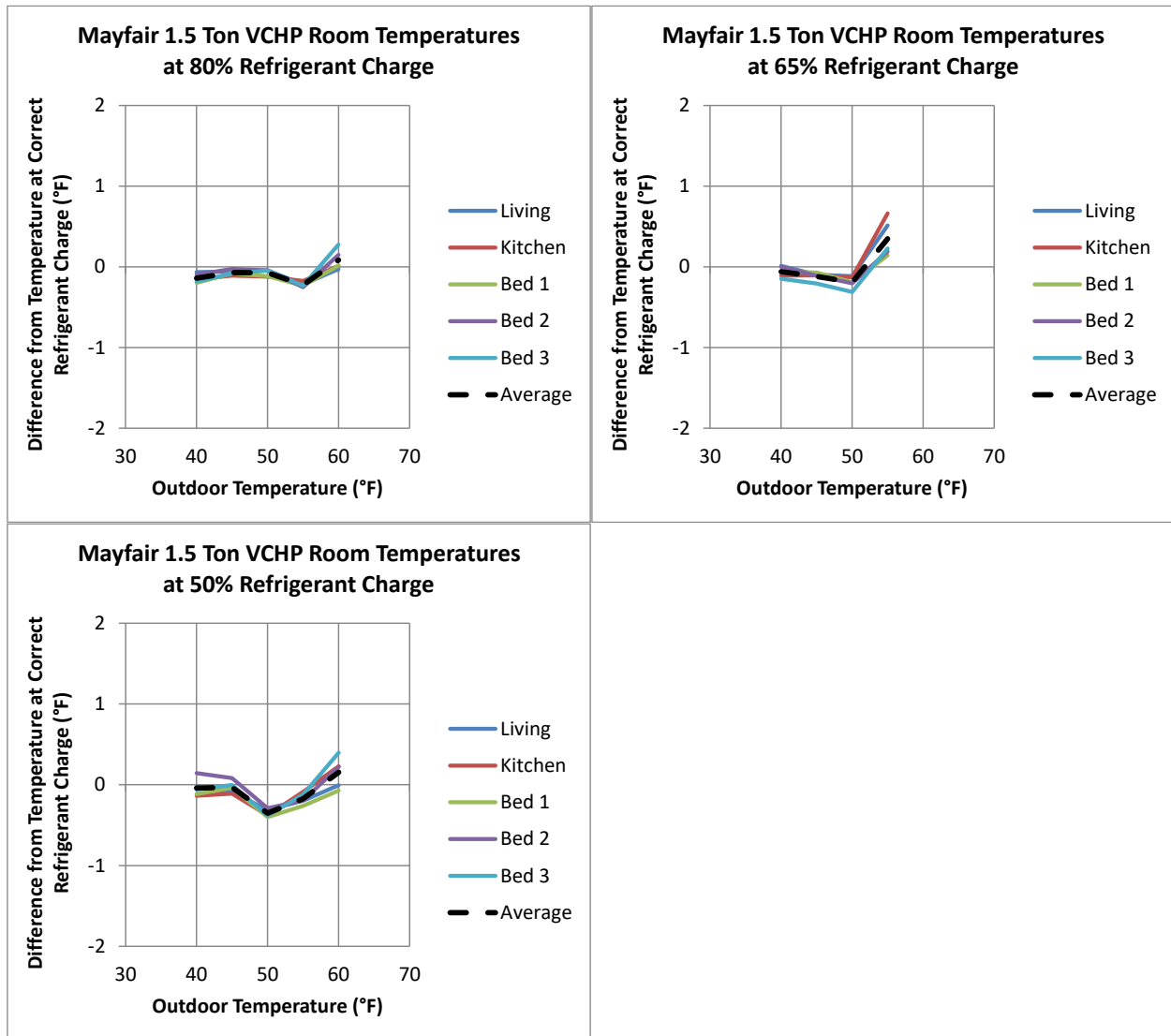


FIGURE 121. MAYFAIR 1.5 TON VCHP HEATING SEASON INDOOR TEMPERATURES AT REFRIGERANT UNDERCHARGE CONDITIONS RELATIVE TO TEMPERATURES AT CORRECT REFRIGERANT CHARGE

Figure 122 and Figure 123 show examples of how this system operated on days with similar outdoor temperature at correct refrigerant charge and at 50% refrigerant charge. Each plotted point represents one minute.

The system was cycling on both days. Three brief periods of higher input power at 2:00 AM, 3:30 AM, and 5:40 AM on the day with 50% refrigerant charge are defrost cycles. Defrost was infrequent, with only 16 defrost cycles observed during the winter, occurring only on the coldest days. 13 of the 16 defrost cycles occurred at 50% refrigerant charge, suggesting that low refrigerant levels may increase defrost mode operation.

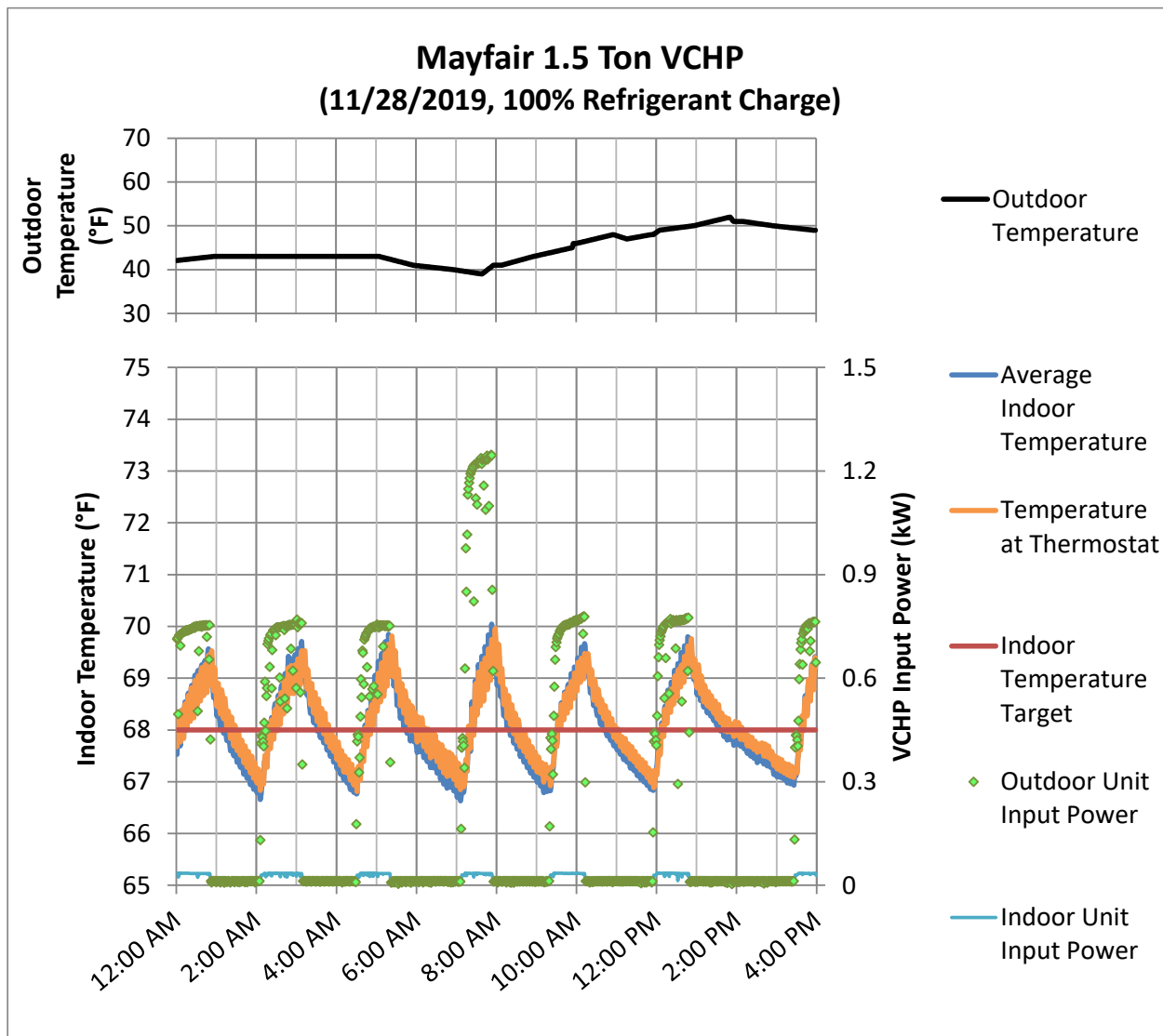


FIGURE 122. MAYFAIR 1.5 TON VCHP HEATING EXAMPLE, CORRECT REFRIGERANT CHARGE

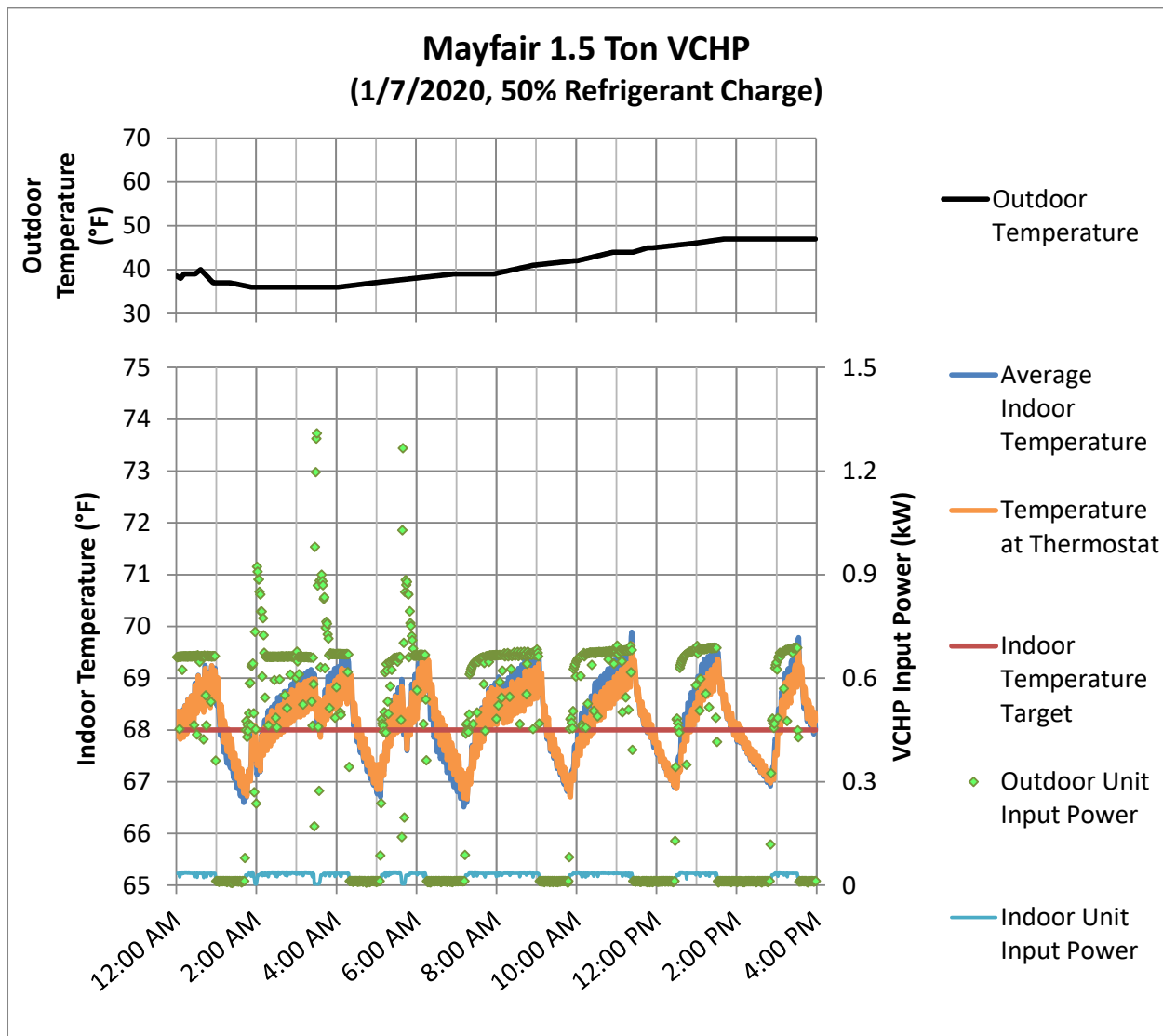


FIGURE 123. MAYFAIR 1.5 TON VCHP HEATING EXAMPLE, 50% REFRIGERANT CHARGE

Figure 124 and Figure 125 show days at 65% and 80% refrigerant charge. The 65% day is warmer due to mild weather throughout the 65% testing period.

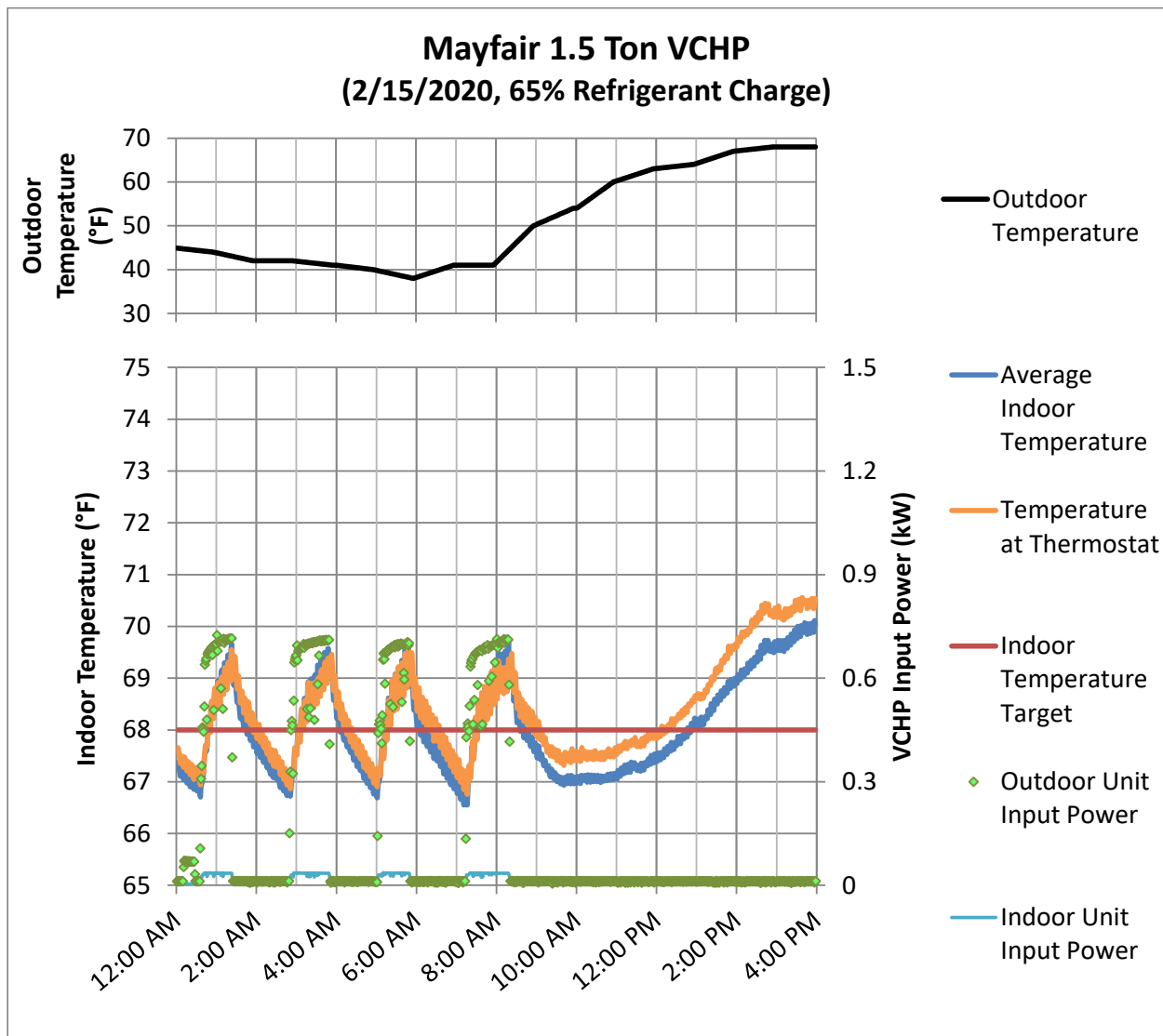


FIGURE 124. MAYFAIR 1.5 TON VCHP HEATING EXAMPLE, 65% REFRIGERANT CHARGE

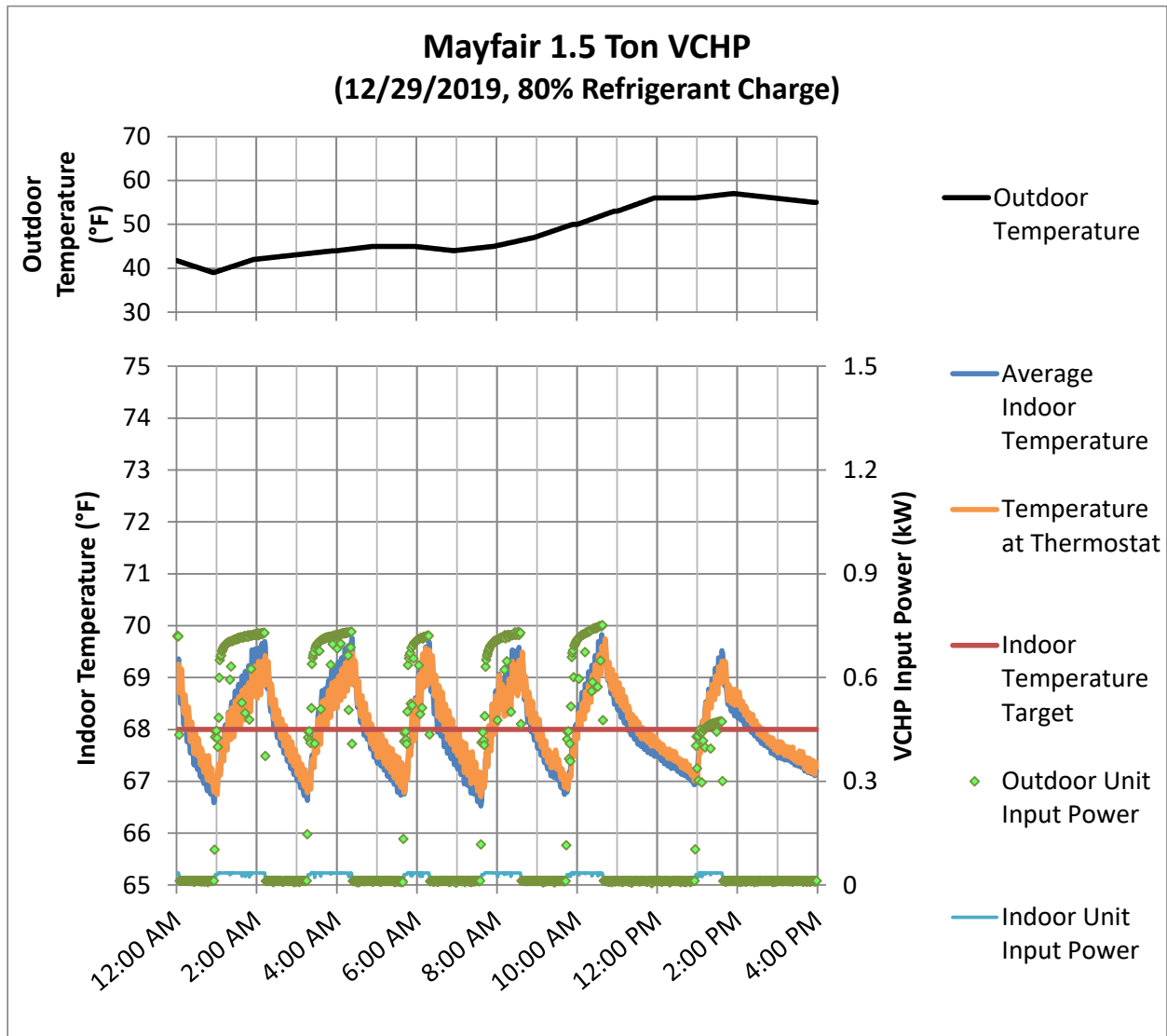


FIGURE 125. MAYFAIR 1.5 TON VCHP HEATING EXAMPLE, 80% REFRIGERANT CHARGE

Figure 126 plots the 1.5 Ton VCHP input power against outdoor temperature at each of the four refrigerant levels. The plotted data includes all days the 1.5 Ton VCHP system operated during the 2019-2020 heating season, and each plotted point represents one minute.

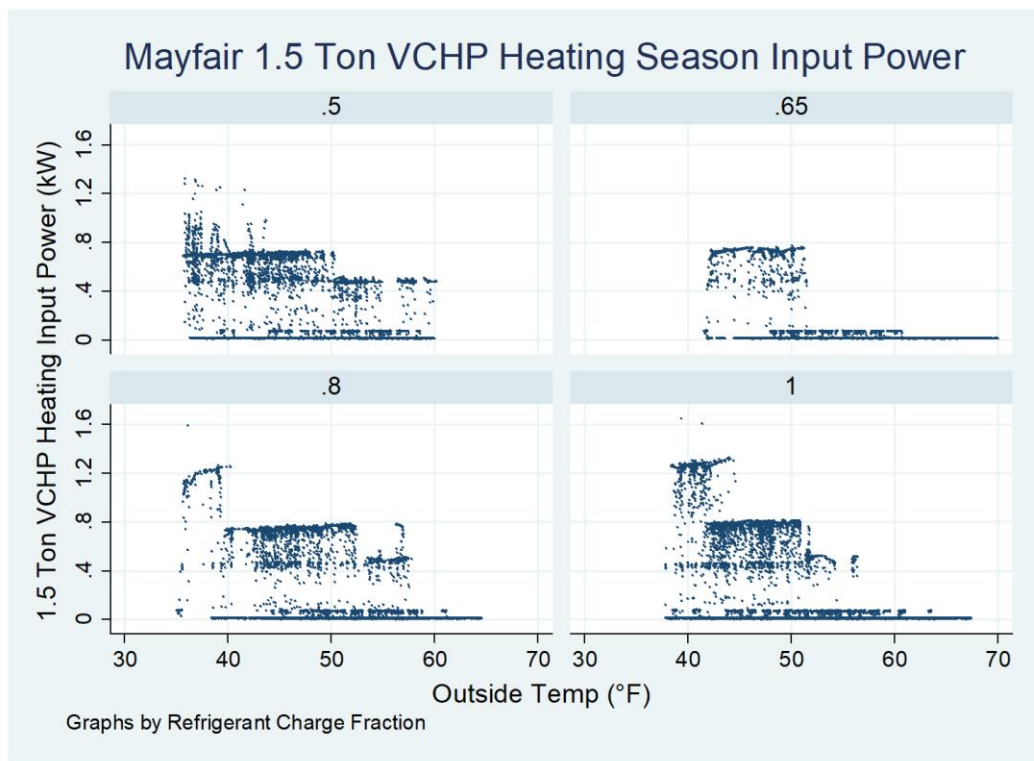


FIGURE 126. MAYFAIR 1.5 TON VCHP INPUT POWER IN HEATING MODE

Cycling characteristics for the 1.5 Ton VCHP at each refrigerant level are tabulated against daily average outdoor temperature in Table 54. There is no clear relationship between refrigerant levels and cycling behavior.

TABLE 54. MAYFAIR 1.5 TON VCHP CYCLING CHARACTERISTICS IN HEATING MODE

	DAILY AVERAGE OUTDOOR TEMPERATURE (°F)	REFRIGERANT LEVEL			
		50%	65%	80%	100%
Average Cycle Length (Minutes)	45	70.4	-	55.2	50.1
	50	56.2	55.0	44.2	55.4
	55	46.0	43.9	37.3	43.8
	60	-	43.1	36.5	40.8
Average Cycles Per Day	45	8.3	-	7.0	8.0
	50	6.3	4.5	7.0	4.3
	55	6.0	2.0	3.0	3.8
	60	-	0.7	1.0	1.0

DAILY ENERGY USE

The daily heating energy use regression results for the 1.5 Ton VCHP are shown in Table 55. Figure 127 displays the monitored and regression predicted daily energy use for each refrigerant level. Figure 128 displays the monitored and regression predicted VCHP daily energy use plotted against daily average outdoor temperature, comparing the modeled results to directly monitored data.

TABLE 55. MAYFAIR 1.5 TON VCHP DAILY HEATING ENERGY REGRESSION

SYSTEM	VARIABLE	COEFFICIENT	t	95% CONFIDENCE INTERVAL	
1.5 Ton VCHP	E _{Ref}	0.1900	13.68	0.1619	0.2181
	E _{Ref_R50}	0.0201	1.68	-0.0041	0.0442
	E _{Ref_R65}	-0.0222	-0.92	-0.0707	0.0264
	E _{Ref_R80}	0.0030	0.22	-0.0241	0.0301
	Constant	0.0431	0.22	-0.3610	0.4472
	R ²	0.90			
	Daily Standby kWh	0.37			
	Total Heating Season Crankcase Heat kWh	13.1			

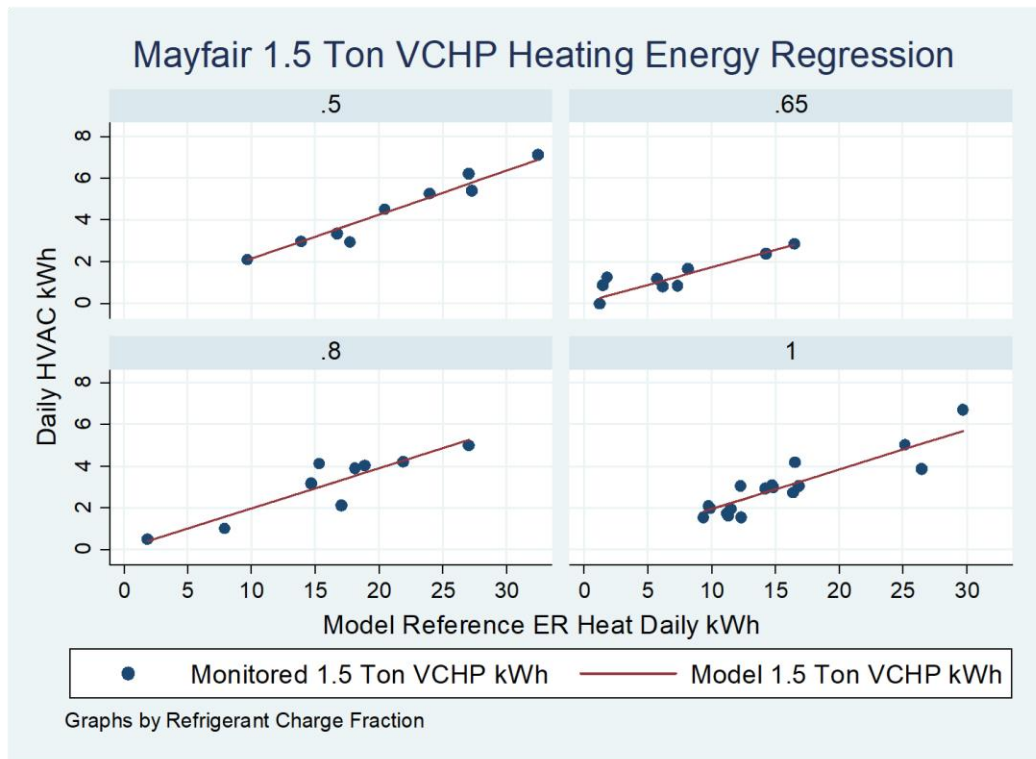


FIGURE 127. MAYFAIR 1.5 TON VCHP DAILY HEATING ENERGY REGRESSION

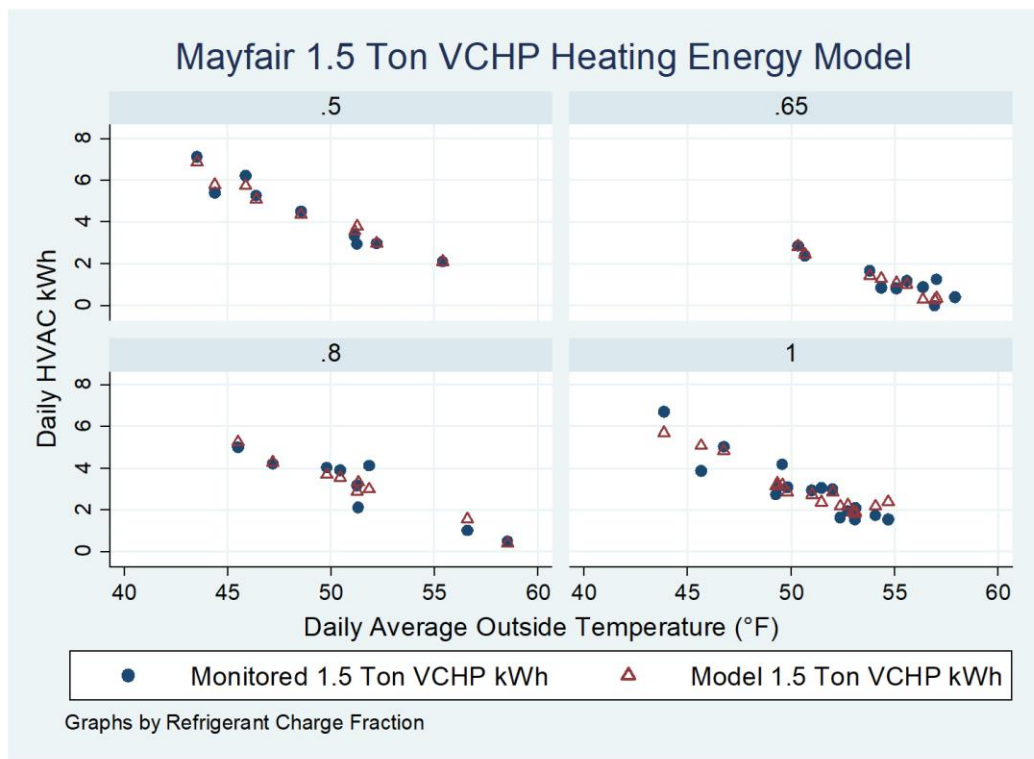


FIGURE 128. MAYFAIR 1.5 TON VCHP MONITORED AND MODEL PREDICTED DAILY HEATING ENERGY

The regression predicted normalized seasonal energy use estimates are shown in Table 56. The daily energy use analysis shows an efficiency reduction at 50% refrigerant charge but little or no loss at lower undercharge levels. The 65% refrigerant level test was limited by mild weather and low heating loads throughout the test period.

TABLE 56. MAYFAIR 1.5 TON VCHP NORMALIZED HEATING SEASON ENERGY USE

SYSTEM	REFRIGERANT LEVEL	SEASONAL ENERGY USE (kWh)	SEASONAL ENERGY USE RELATIVE TO CORRECT REFRIGERANT CHARGE	IMPLIED EFFICIENCY RELATIVE TO CORRECT REFRIGERANT CHARGE
1.5 Ton VCHP	50%	723.5	109%	92%
	65%	594.3	90%	111%
	80%	671.3	101%	99%
	100%	662.1	100%	100%

MAYFAIR HOUSE, 2 TON VCHP

COOLING SEASON

The 2 Ton VCHP system maintained similar indoor temperatures at all refrigerant levels. Average temperatures of each room relative to the target temperature are shown in Figure 129. Average indoor temperatures relative to the temperatures at correct refrigerant charge are shown in Figure 130.

The plotted values represent the average of all minutes that occurred during hours with compressor operation during the hour, indicating that the system was providing cooling to the house during the hour. This system is controlled by a single thermostat located in the living room.

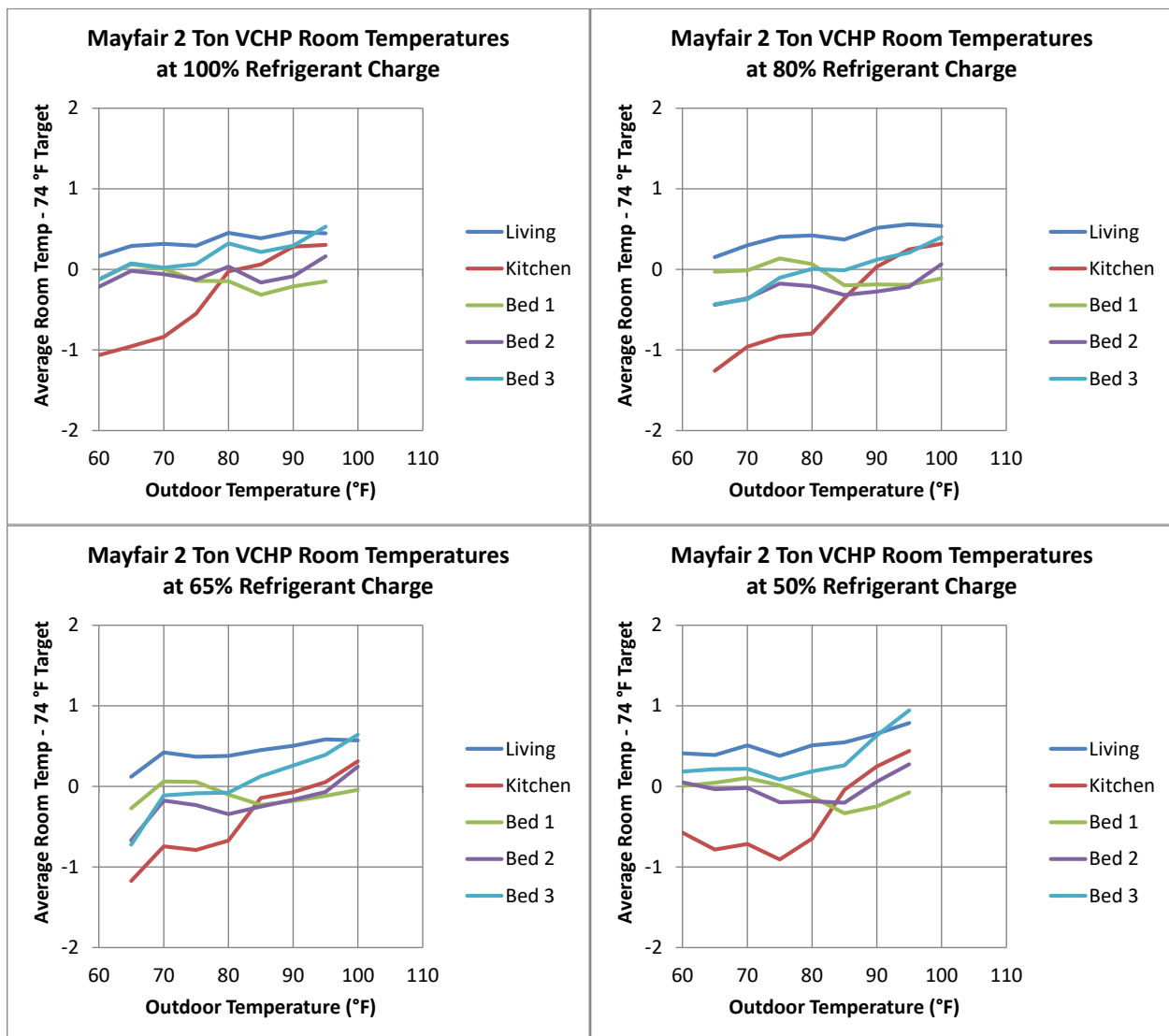


FIGURE 129. MAYFAIR 2 TON VCHP COOLING SEASON INDOOR TEMPERATURE DELTA TO TARGET

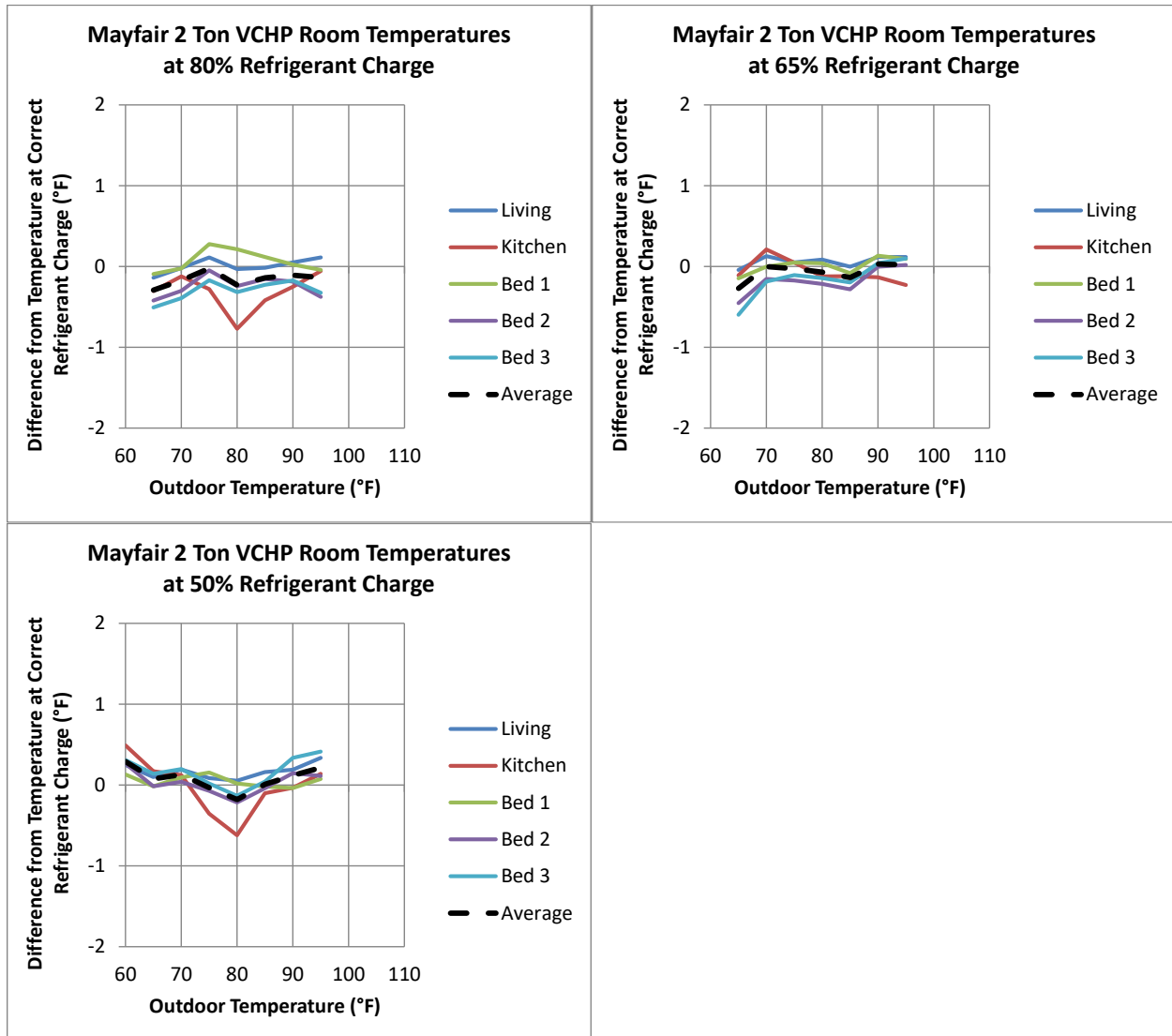


FIGURE 130. MAYFAIR 2 TON VCHP COOLING SEASON INDOOR TEMPERATURES AT REFRIGERANT UNDERCHARGE CONDITIONS RELATIVE TO TEMPERATURES AT CORRECT REFRIGERANT CHARGE

Figure 131 and Figure 132 show examples of how this system operated on days with similar outdoor temperature at correct refrigerant charge and at 50% refrigerant charge. Each plotted point represents one minute.

In the morning of both days, when outdoor temperatures were mild and cooling loads were low, the system cycled and maintained indoor temperatures near target. At 100% refrigerant charge, the system continued to cycle throughout the day. At 50% refrigerant charge, it settled into constant low speed operation during the afternoon.

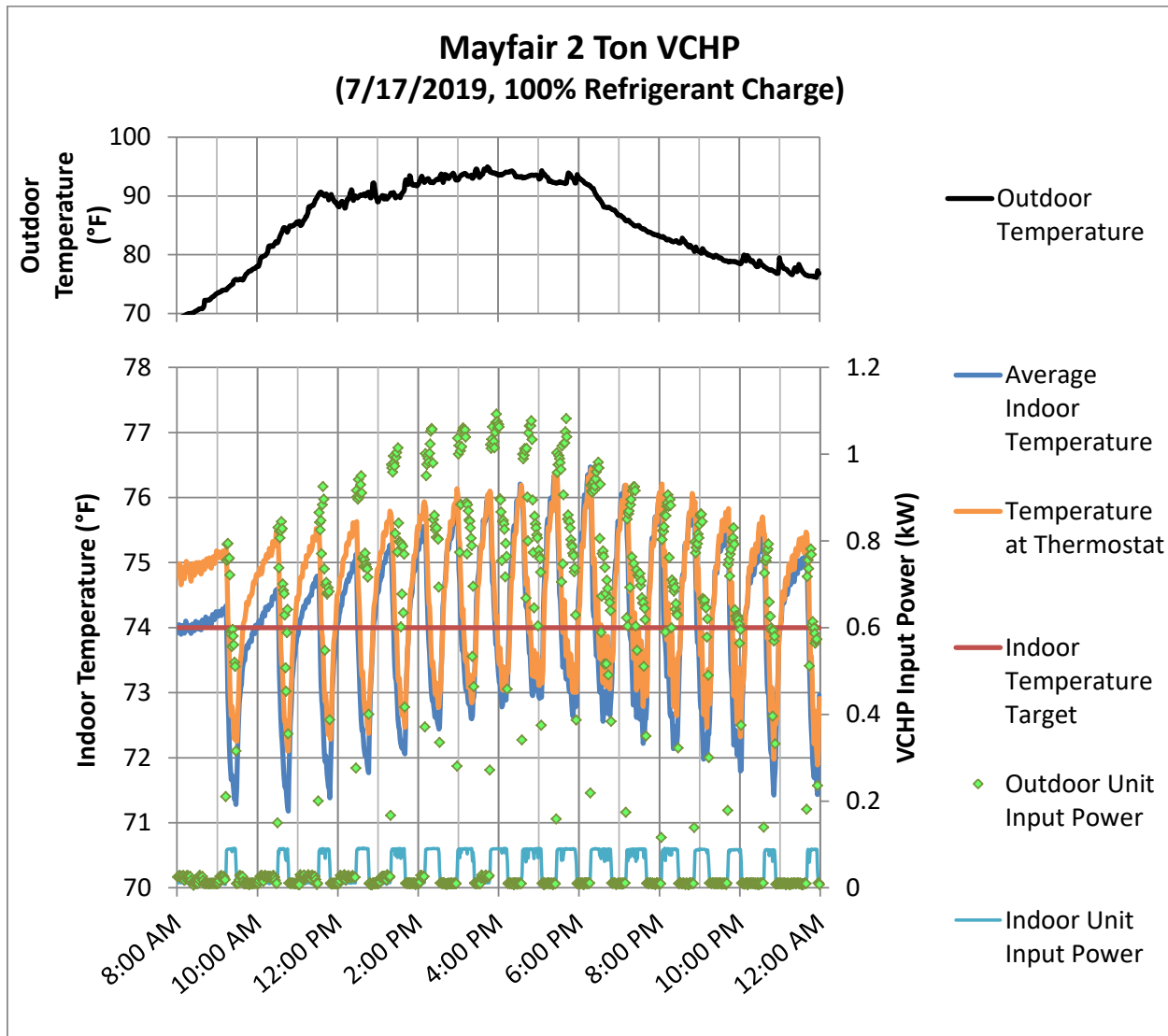


FIGURE 131. MAYFAIR 2 TON VCHP COOLING EXAMPLE, CORRECT REFRIGERANT CHARGE

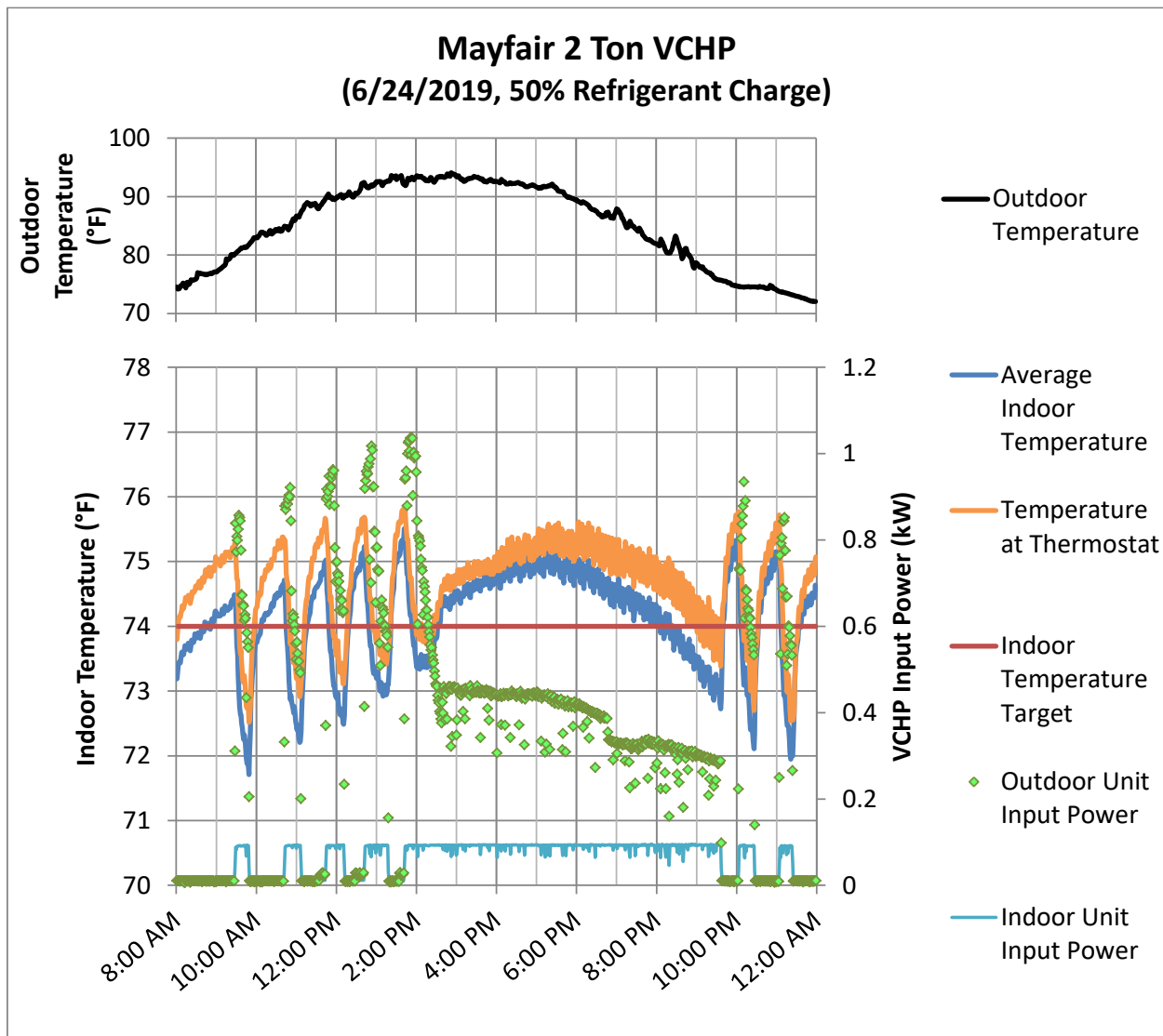


FIGURE 132. MAYFAIR 2 TON VCHP COOLING EXAMPLE, 50% REFRIGERANT CHARGE

Figure 133 and Figure 134 show similar days at 65% and 80% refrigerant charge.

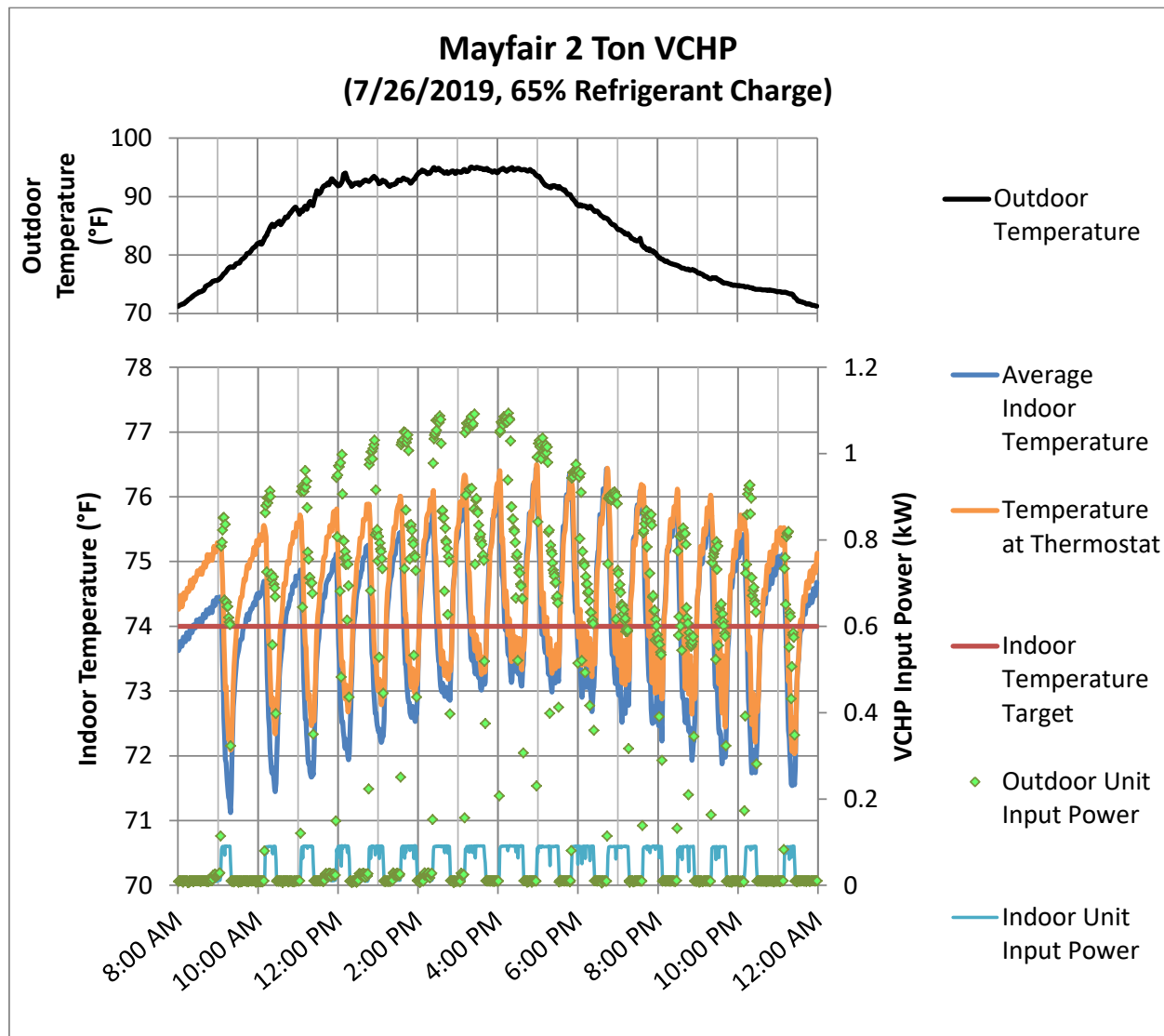


FIGURE 133. MAYFAIR 2 TON VCHP COOLING EXAMPLE, 65% REFRIGERANT CHARGE

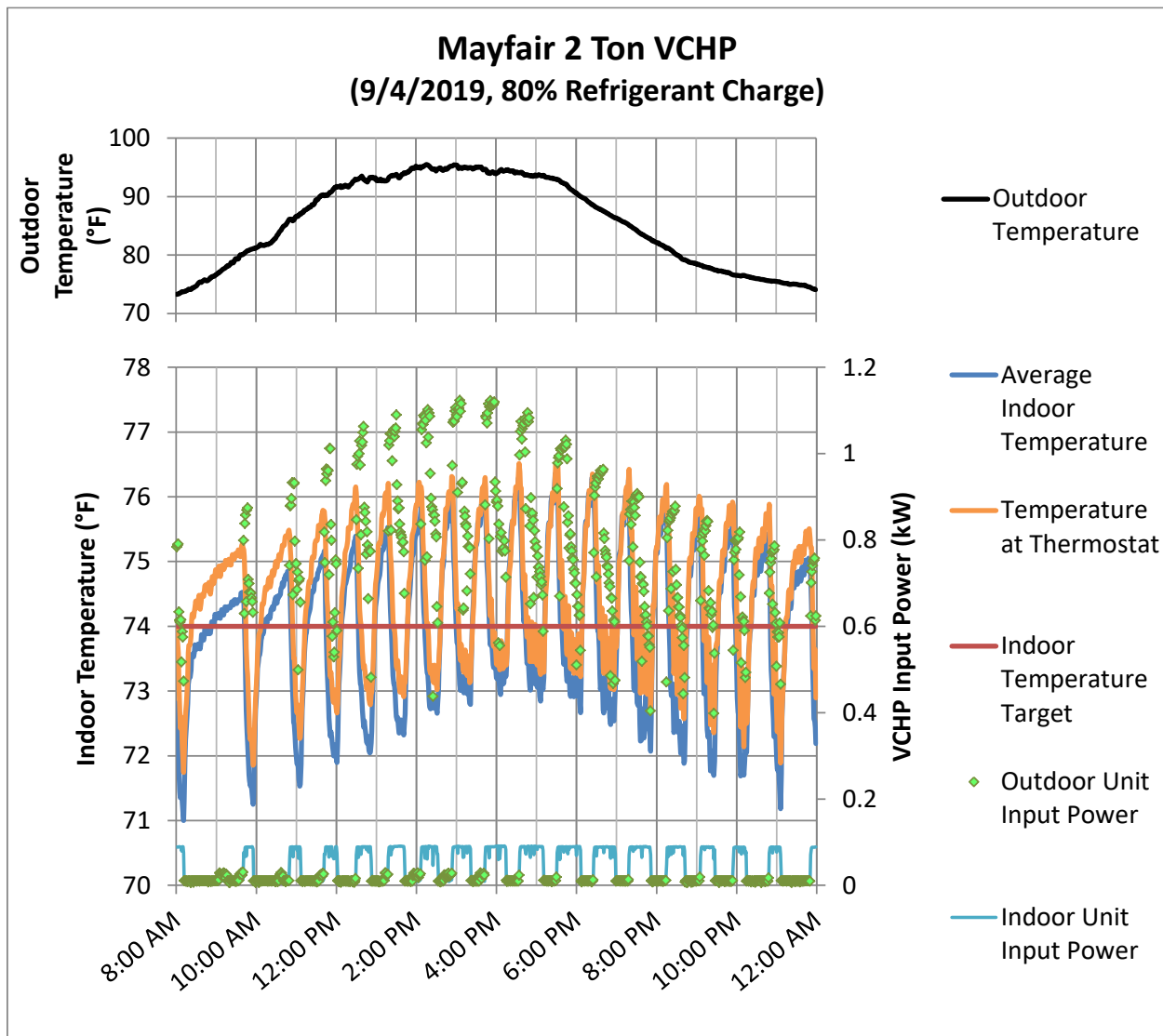


FIGURE 134. MAYFAIR 2 TON VCHP COOLING CAPACITY MODULATION EXAMPLE, 80% REFRIGERANT CHARGE

Figure 135 plots the 2 ton VCHP input power against outdoor temperature at each of the four refrigerant levels. The plotted data includes all days the 2 ton VCHP system operated during the 2019 cooling season, and each plotted point represents one minute.

The two prominent groupings of data points on each plot represent compressor speed/capacity ramping during each cycle. This unit started each cycle at a higher input power, and then power decreased by about 200W after several minutes, as shown in Figure 136.

There is also a third, lower grouping of data points at about 0.4 kW visible on the 50% and 65% refrigerant charge plots. This is the lower speed/capacity seen in Figure 132 during the afternoon. This lower speed was observed only occasionally and only at low refrigerant levels when capacity was sufficiently reduced for the system to begin operating continuously instead of cycling on hot afternoons.

As with the 1.5 ton VCHP, input power for this unit also increased at outdoor temperatures below about 75 °F, but the increase was much smaller for the 2 ton VCHP than for the 1.5 ton system.

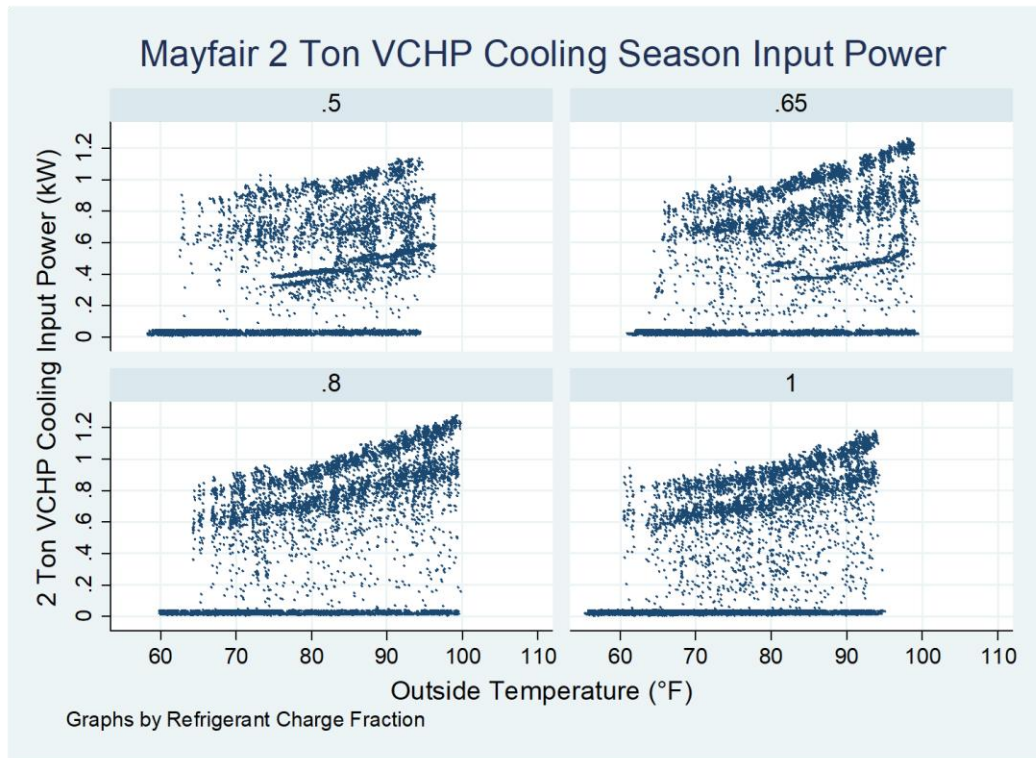


FIGURE 135. MAYFAIR 2 TON VCHP INPUT POWER IN COOLING MODE

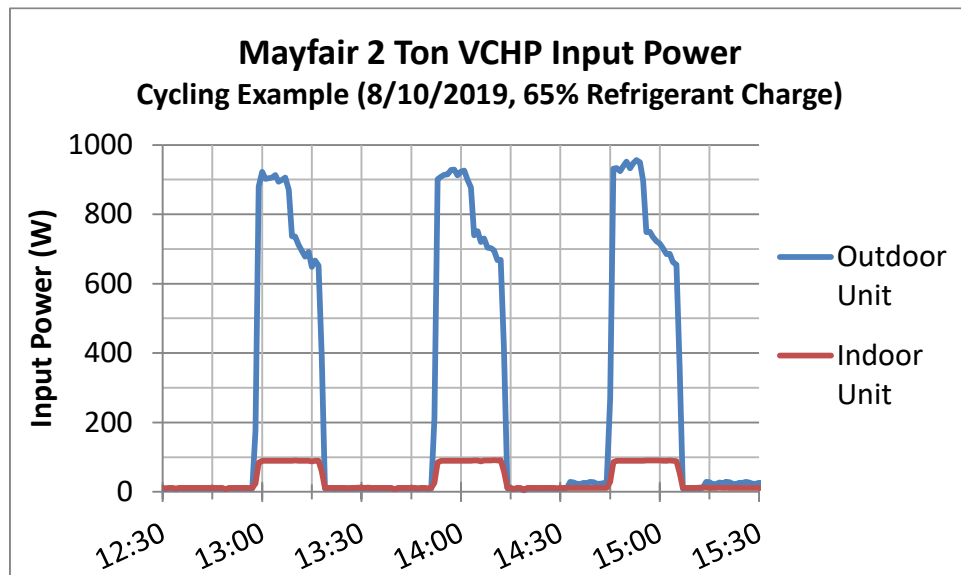


FIGURE 136. MAYFAIR 2 TON VCHP CYCLING EXAMPLE, COOLING MODE

Cycling characteristics for the 2 Ton VCHP at each refrigerant level are tabulated against daily average outdoor temperature in Table 57. Cycle length increased at very low refrigerant levels. This system did not run very short or very frequent cycles under any conditions.

TABLE 57. MAYFAIR 2 TON VCHP CYCLING CHARACTERISTICS IN COOLING MODE

	DAILY AVERAGE OUTDOOR TEMPERATURE (°F)	REFRIGERANT LEVEL			
		50%	65%	80%	100%
Average Cycle Length (Minutes)	70	27.7	-	19.7	17.8
	75	38.6	21.0	21.1	20.2
	80	85.2	31.1	22.3	20.8
	85	-	34.6	24.7	-
Average Cycles Per Day	70	11.5	-	15.5	10.1
	75	10.8	16.4	21.0	15.0
	80	7.7	18.5	22.0	19.0
	85	-	19.0	21.5	-

DAILY ENERGY USE

The daily cooling energy use regression results for the 2 Ton VCHP are shown in Table 58. Figure 137 displays the monitored and regression predicted daily energy use for each refrigerant level. Figure 138 displays the monitored and regression predicted VCHP daily energy use plotted against daily average outdoor temperature, comparing the modeled results to directly monitored data.

TABLE 58. MAYFAIR 2 TON VCHP DAILY COOLING ENERGY USE REGRESSION

SYSTEM	VARIABLE	COEFFICIENT	t	95% CONFIDENCE INTERVAL	
2 Ton VCHP	E _{Ref}	0.5746	18.02	0.5100	0.6392
	E _{Ref_R50}	0.1248	5.11	0.0753	0.1743
	E _{Ref_R65}	0.0788	3.42	0.0321	0.1256
	E _{Ref_R80}	0.0704	3.06	0.0238	0.1170
	Constant	0.4015	2.38	0.0601	0.7429
	R ²	0.97			
	Daily Standby kWh	0.51			
	Total Cooling Season Crankcase Heat kWh	9			

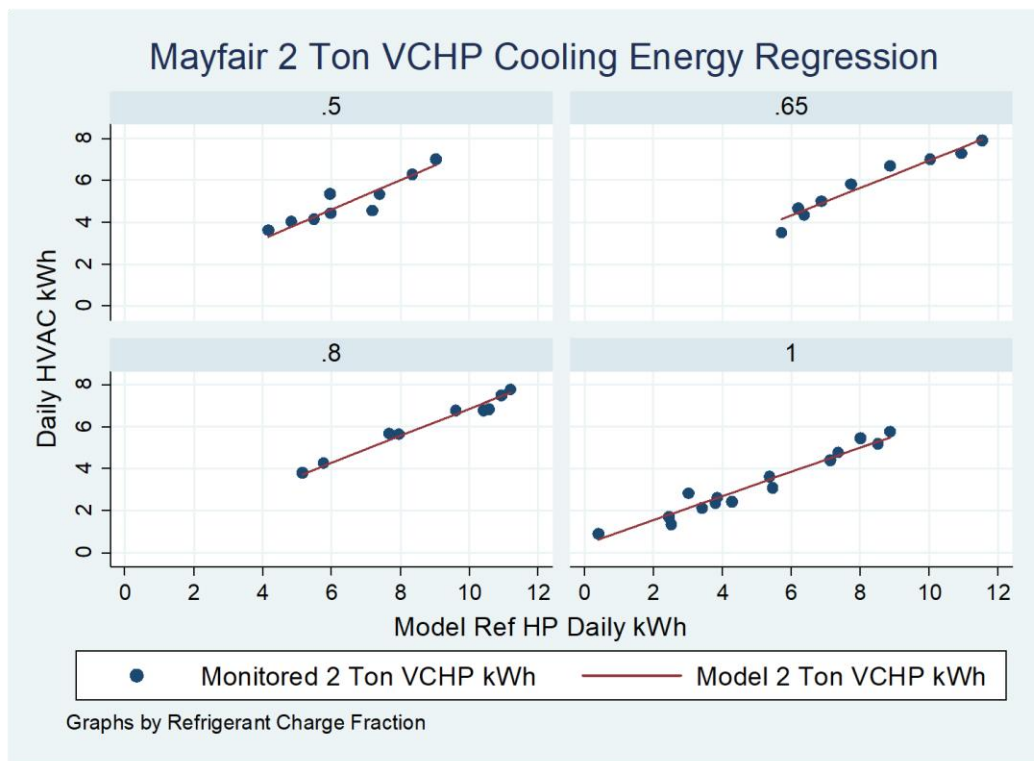


FIGURE 137. MAYFAIR 2 TON VCHP DAILY COOLING ENERGY REGRESSION

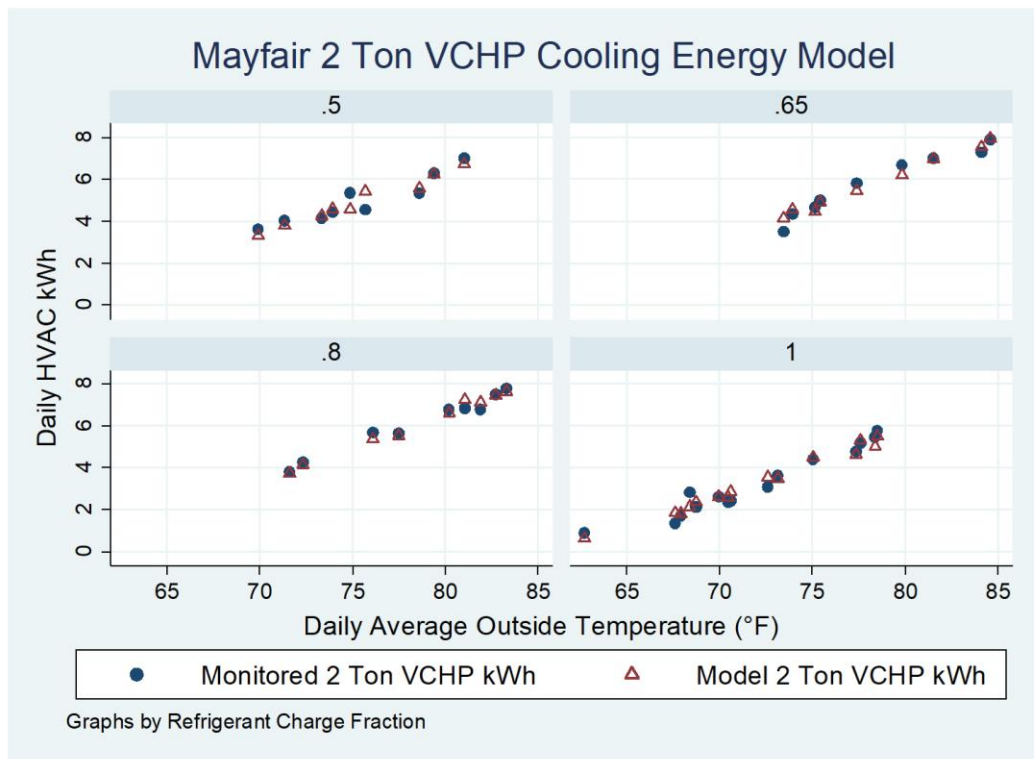


FIGURE 138. MAYFAIR 2 TON VCHP MONITORED AND MODEL PREDICTED DAILY COOLING ENERGY

The regression predicted normalized seasonal energy use estimates are shown in Table 59. The daily energy use analysis shows efficiency reductions at all three refrigerant undercharge levels, with a loss of 14% at 50% refrigerant charge.

TABLE 59. MAYFAIR 2 TON VCHP NORMALIZED COOLING SEASON ENERGY USE

SYSTEM	REFRIGERANT LEVEL	SEASONAL ENERGY USE (kWh)	SEASONAL ENERGY USE RELATIVE TO CORRECT REFRIGERANT CHARGE	IMPLIED EFFICIENCY RELATIVE TO CORRECT REFRIGERANT CHARGE
2 Ton VCHP	50%	750.2	117%	86%
	65%	710.8	111%	90%
	80%	703.5	109%	91%
	100%	643.1	100%	100%

AFTERNOON AND EVENING DEMAND

Refrigerant undercharge increased afternoon and evening demand of the 2 ton VCHP during most hours. In some cases, demand reductions occurred. Average hourly demand relative to performance at correct refrigerant charge is tabulated in Table 60. The monitored energy use during each hour for each refrigerant level is plotted in Figure 139.

TABLE 60. MAYFAIR 2 TON VCHP AVERAGE HOURLY DEMAND RELATIVE TO PERFORMANCE AT CORRECT REFRIGERANT CHARGE

REFRIGERANT LEVEL	HOUR	HOURLY AVERAGE OUTDOOR TEMPERATURE (°F)				
		80	85	90	95	100
50%	2-3 PM		125%	143%	122%	-
	3-4 PM	111%	160%	109%	96%	-
	4-5 PM	134%	141%	101%	114%	-
	5-6 PM	154%	130%	106%	133%	-
	6-7 PM	121%	118%	104%	-	-
	7-8 PM	107%	132%	-	-	-
	8-9 PM	86%	-	-	-	-
	9-10 PM	89%	-	-	-	-
65%	2-3 PM	-	112%	125%	94%	-
	3-4 PM	-	122%	80%	81%	-
	4-5 PM	-	107%	74%	110%	-
	5-6 PM	117%	127%	116%	107%	-
	6-7 PM	117%	159%	115%	-	-
	7-8 PM	127%	124%	-	-	-
	8-9 PM	86%	-	-	-	-
	9-10 PM	101%	-	-	-	-
80%	2-3 PM	-	135%	147%	127%	-
	3-4 PM	-	124%	110%	109%	-
	4-5 PM	-	109%	83%	104%	-
	5-6 PM	129%	99%	94%	108%	-
	6-7 PM	118%	142%	117%	-	-
	7-8 PM	131%	138%	-	-	-
	8-9 PM	99%	-	-	-	-
	9-10 PM	93%	-	-	-	-

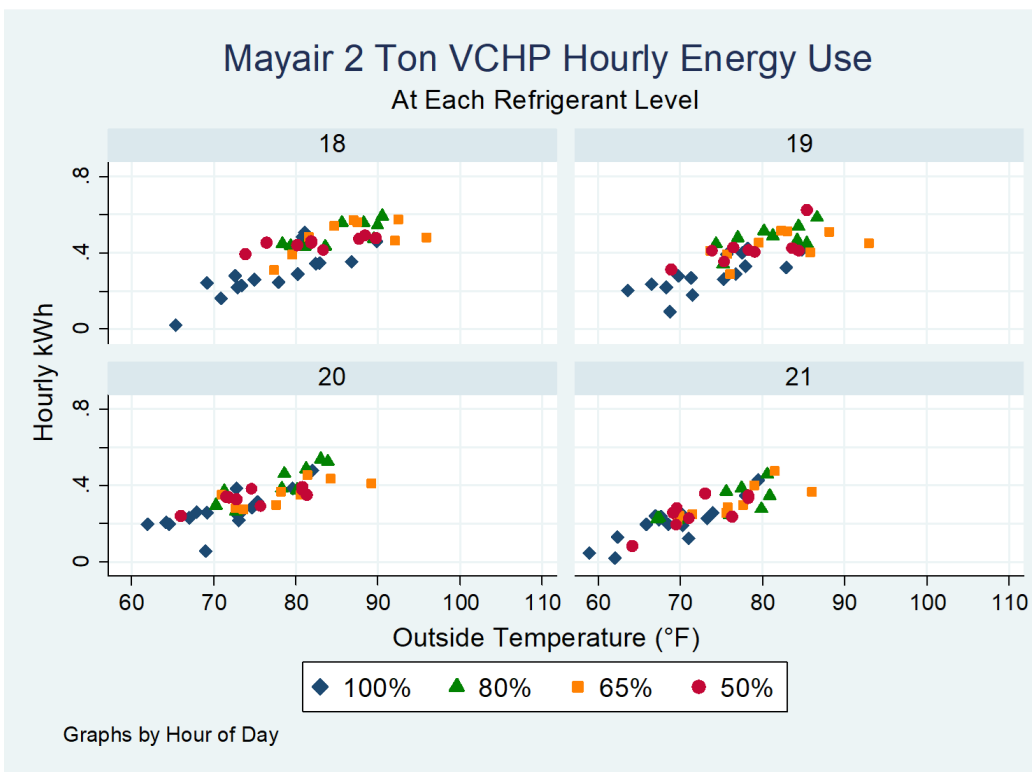
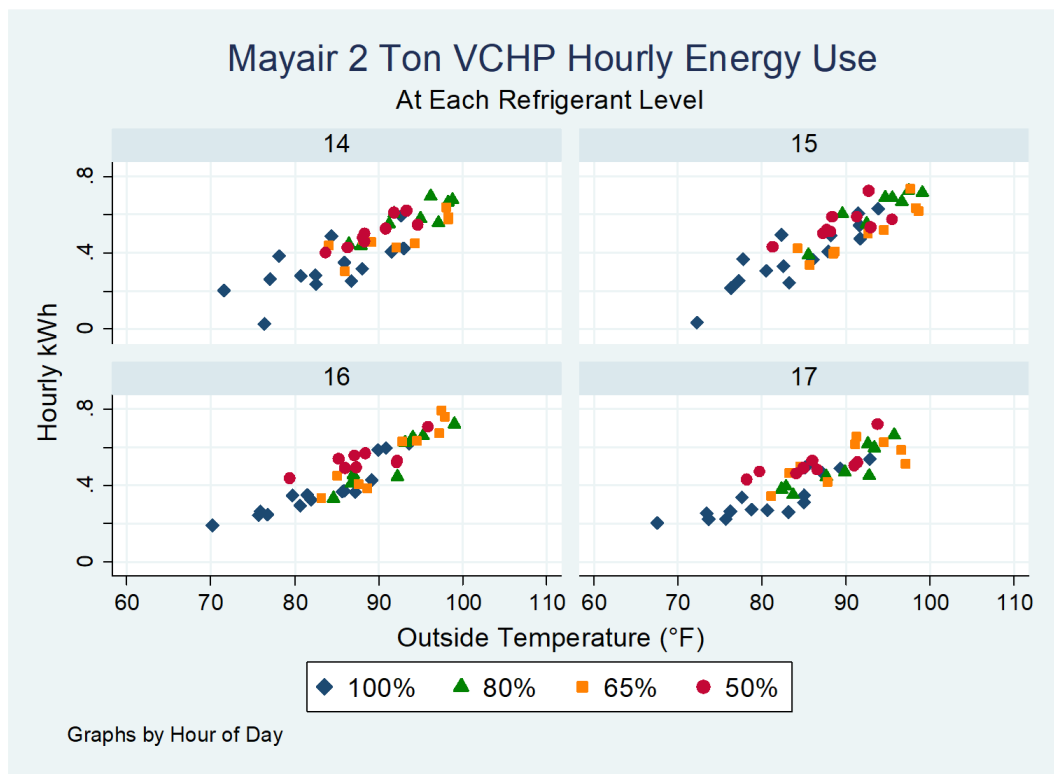


FIGURE 139. MAYFAIR COOLING SEASON 2 TON VCHP HOURLY ENERGY USE AT EACH REFRIGERANT LEVEL

HEATING SEASON

The 2 Ton VCHP system maintained similar indoor temperatures at all refrigerant levels. Average temperatures of each room relative to the target temperature are shown in Figure 140. Average indoor temperatures relative to the temperatures at correct refrigerant charge are shown in Figure 141. The plotted values represent the average of all minutes that occurred during hours with compressor operation during the hour, indicating that the system was providing heating to the house during the hour.

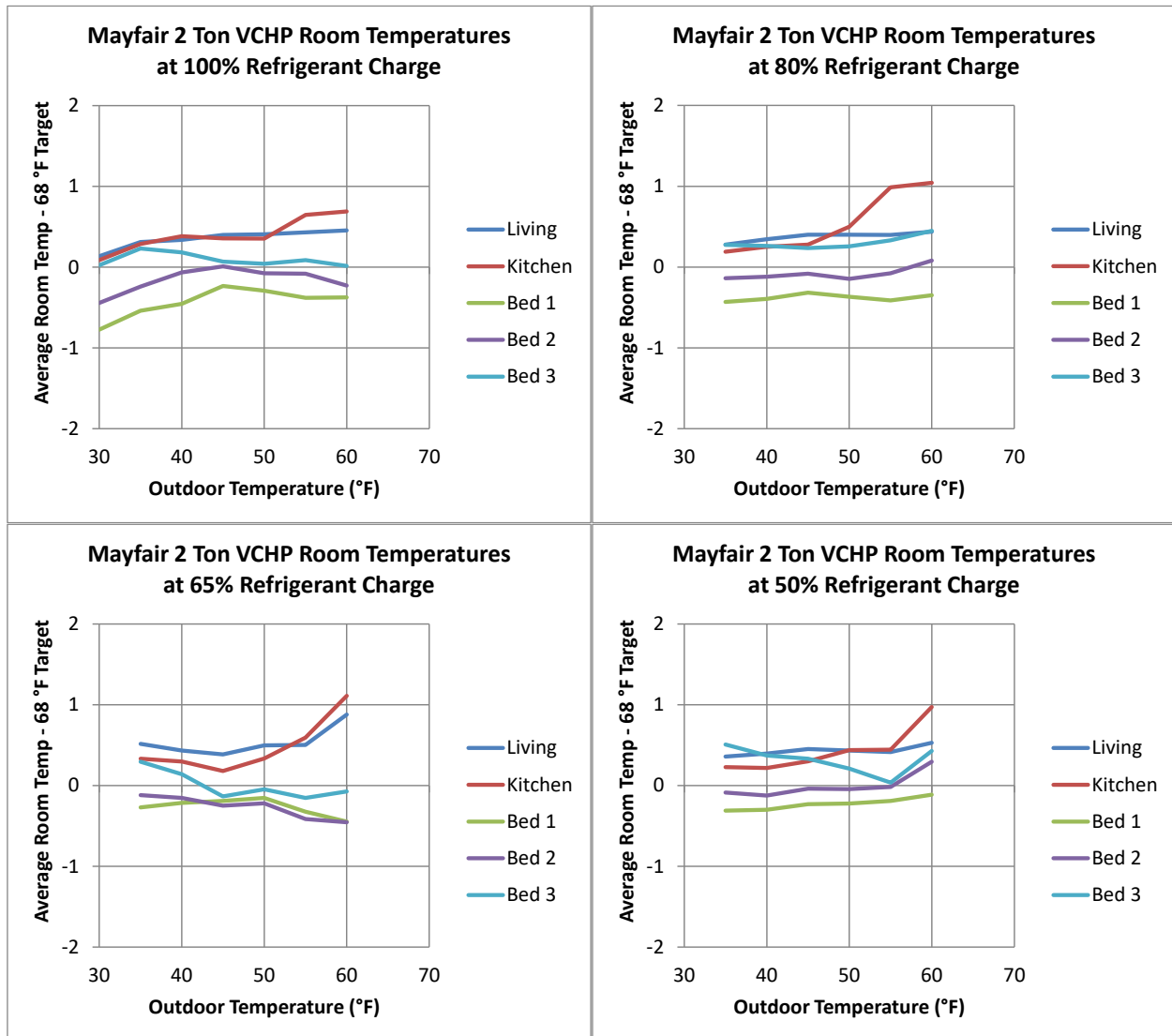


FIGURE 140. MAYFAIR 2 TON VCHP HEATING SEASON INDOOR TEMPERATURE DELTA TO TARGET

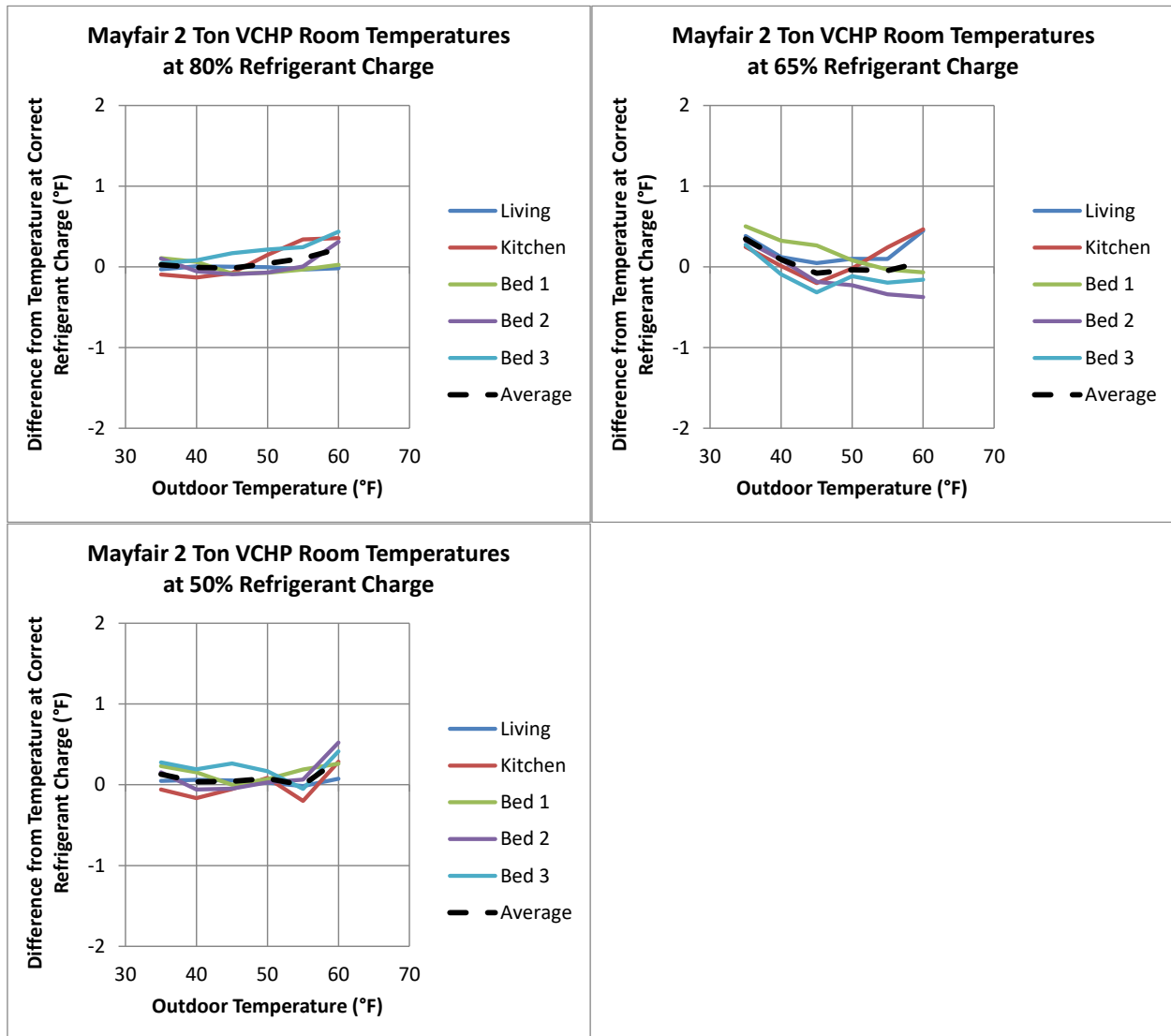


FIGURE 141. MAYFAIR 2 TON VCHP HEATING SEASON INDOOR TEMPERATURES AT REFRIGERANT UNDERCHARGE CONDITIONS RELATIVE TO TEMPERATURES AT CORRECT REFRIGERANT CHARGE

Figure 142 and Figure 143 show examples of how this system operated on days with similar outdoor temperature at correct refrigerant charge and at 50% refrigerant charge. Each plotted point represents one minute. The system was cycling on both days.

Defrost cycles were infrequent, with only 3 observed during the heating season.

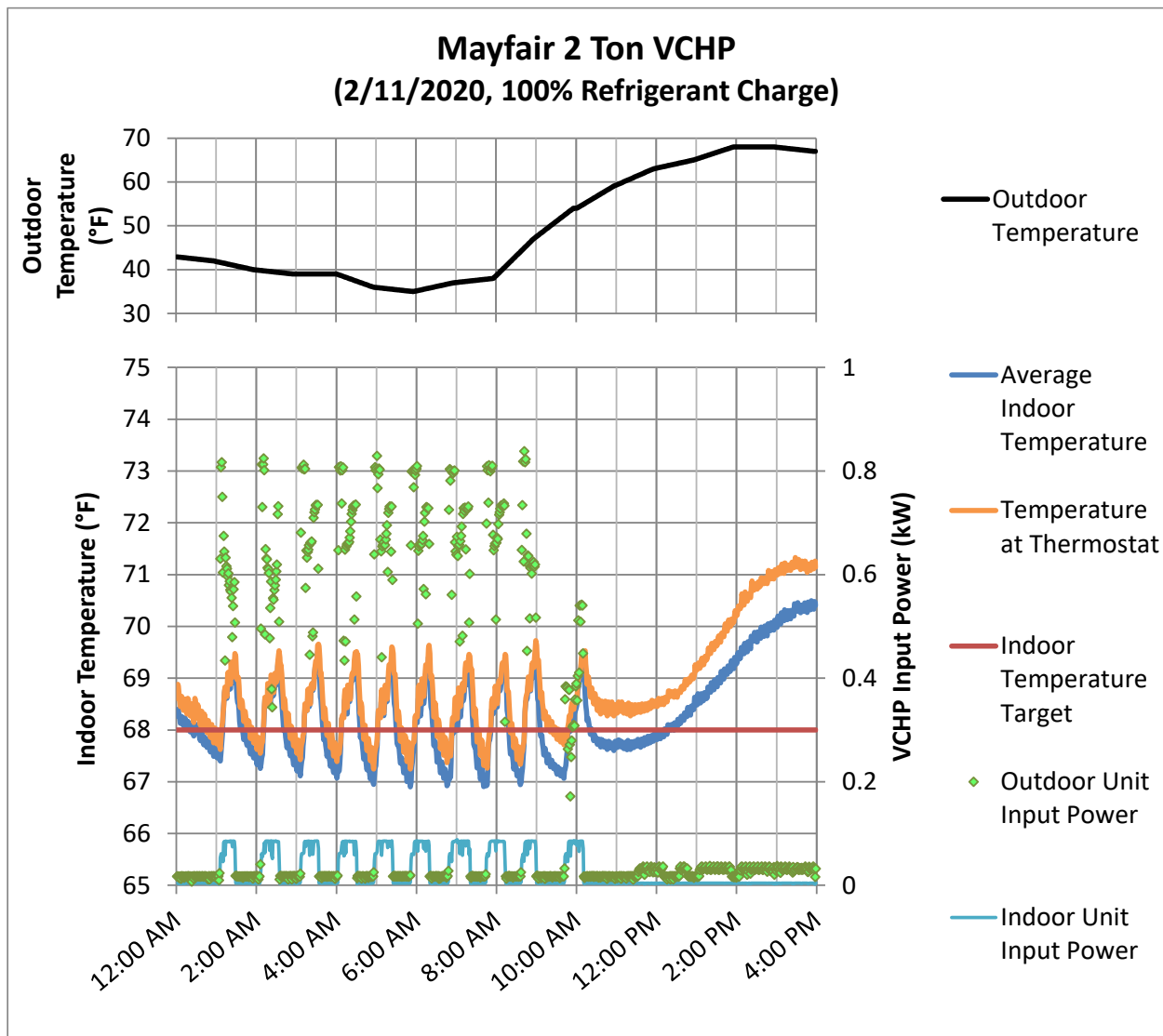


FIGURE 142. MAYFAIR 2 TON VCHP HEATING EXAMPLE, CORRECT REFRIGERANT CHARGE

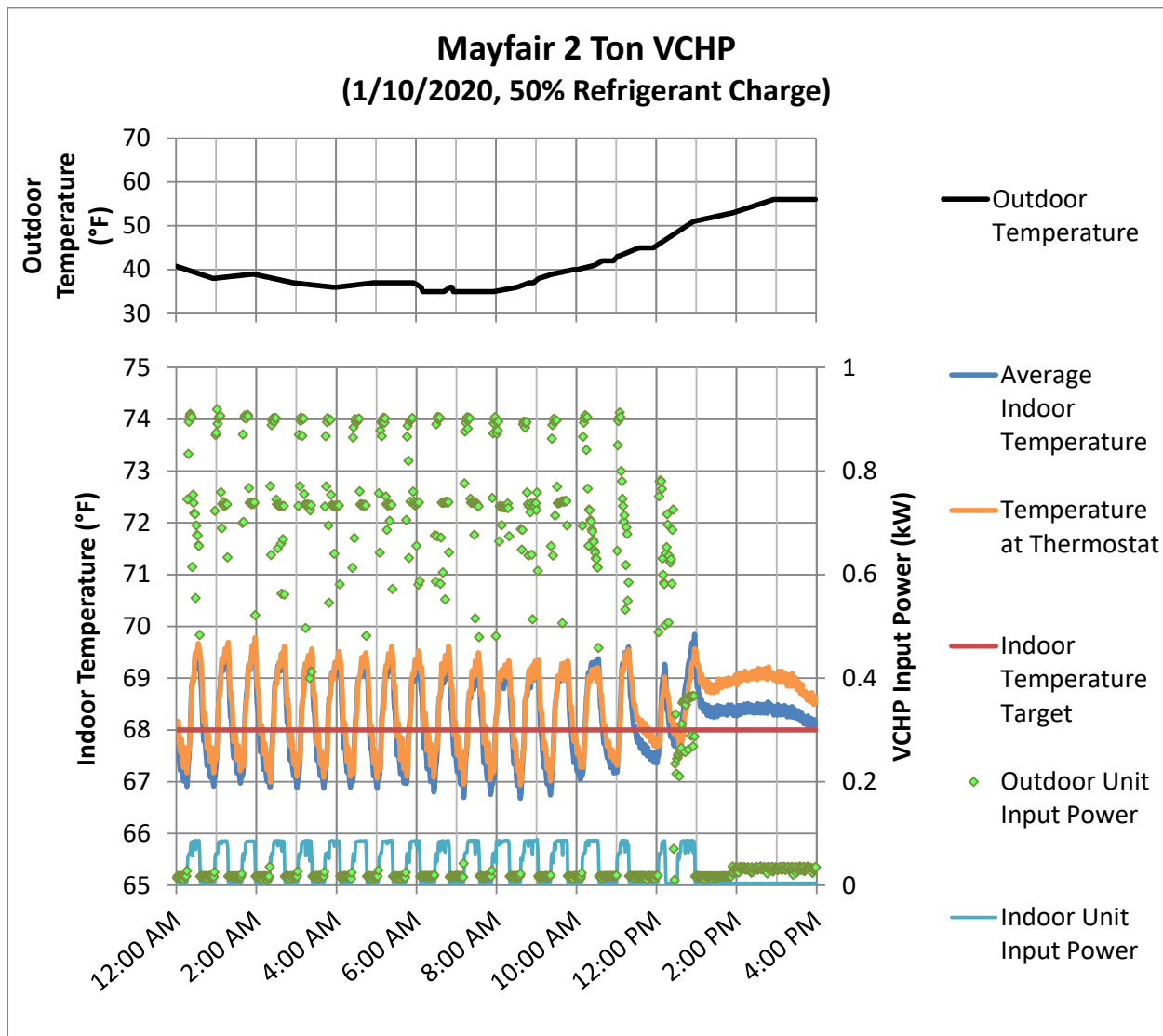


FIGURE 143. MAYFAIR 2 TON VCHP HEATING EXAMPLE, 50% REFRIGERANT CHARGE

Figure 144 and Figure 145 show days at 65% and 80% refrigerant charge. The 65% day is warmer due to mild weather throughout the 65% testing period.

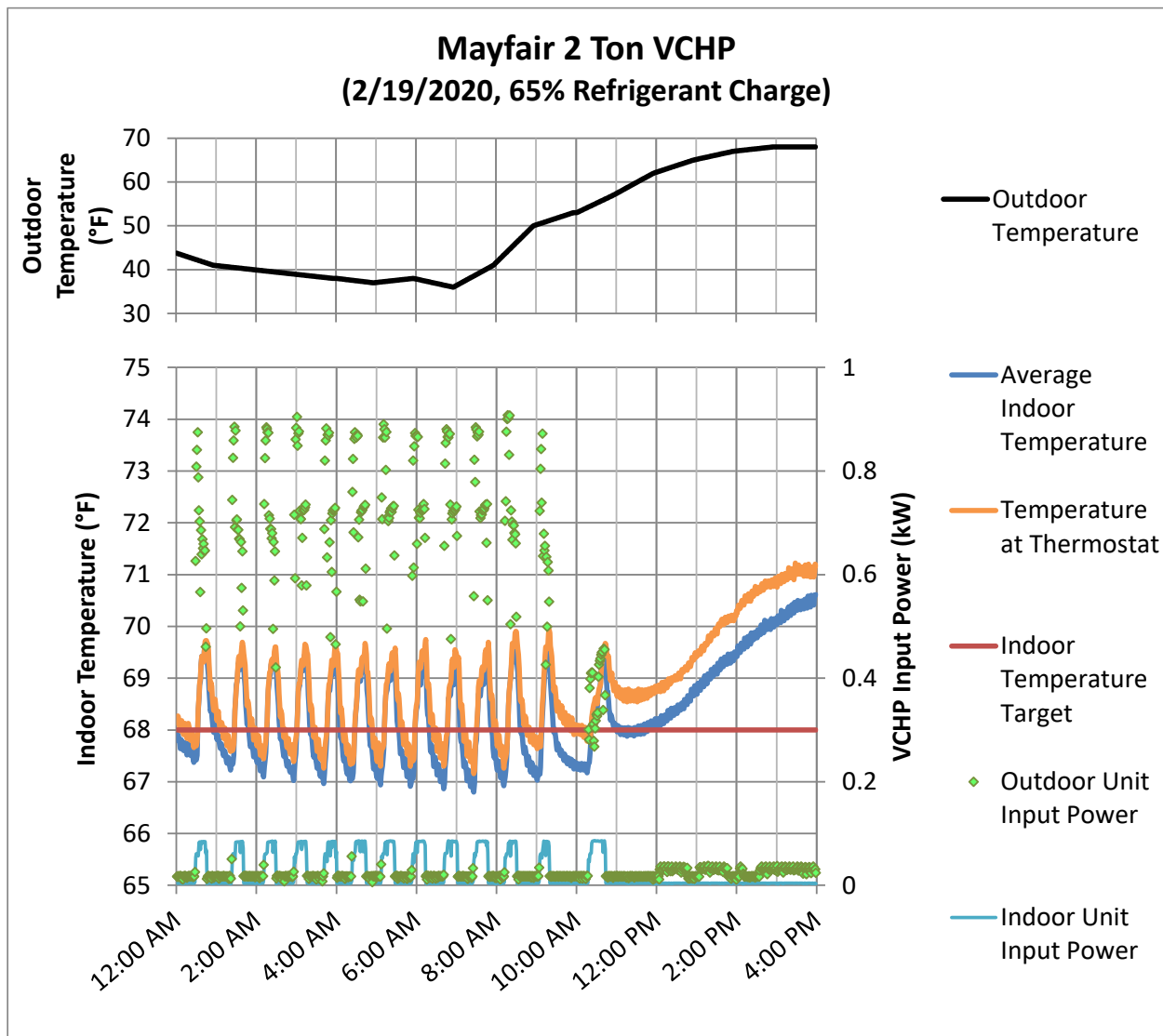


FIGURE 144. MAYFAIR 2 TON VCHP HEATING EXAMPLE, 65% REFRIGERANT CHARGE

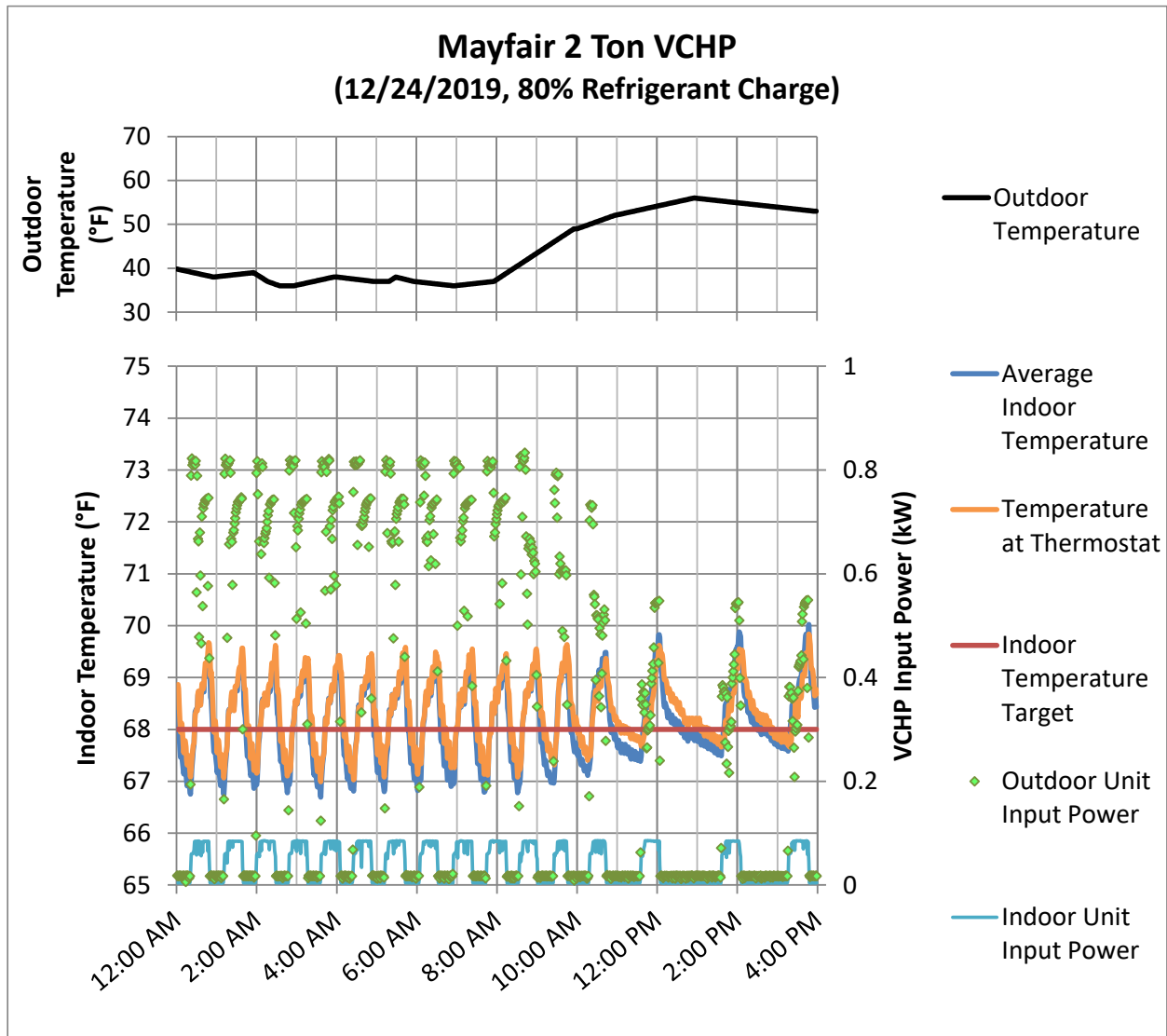


FIGURE 145. MAYFAIR 2 TON VCHP HEATING EXAMPLE, 80% REFRIGERANT CHARGE

Figure 146 plots the 2 Ton VCHP input power against outdoor temperature at each of the four refrigerant levels. The plotted data includes all days the 2 Ton VCHP system operated during the 2019-2020 heating season, and each plotted point represents one minute. The two clusters of points at each refrigerant level reflect cycling behavior similar to cooling mode, with each cycle starting at a higher speed and then dropping to a lower speed after several minutes.

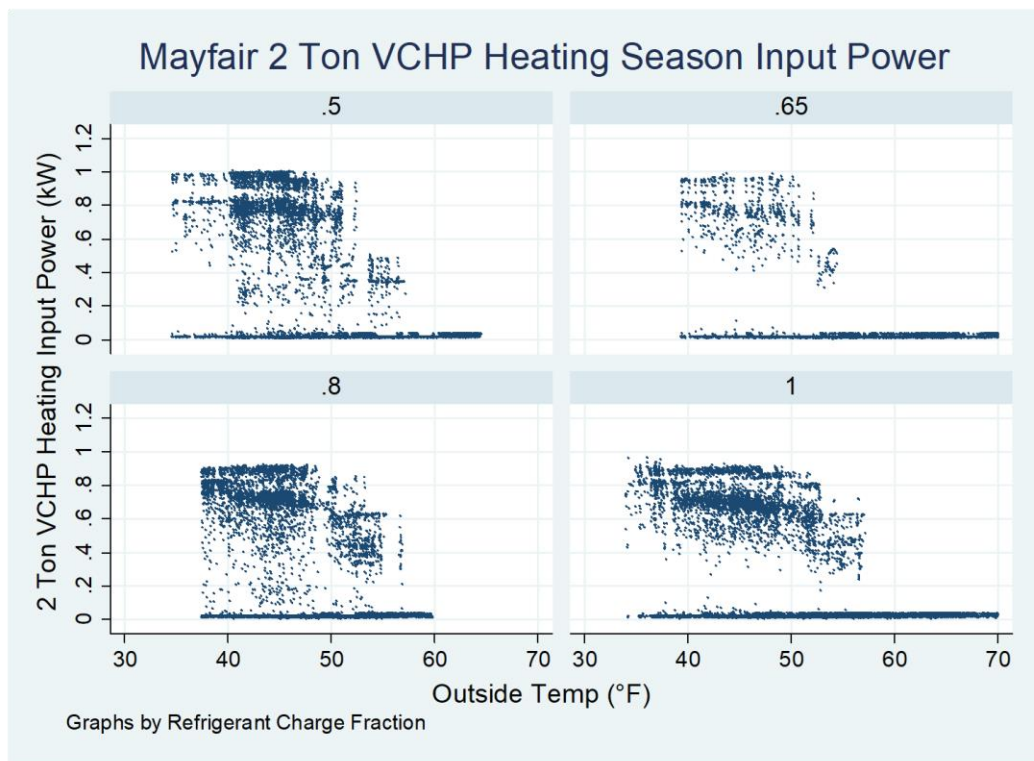


FIGURE 146. MAYFAIR 2 TON VCHP INPUT POWER IN HEATING MODE

Cycling characteristics for the 2 Ton VCHP at each refrigerant level are tabulated against daily average outdoor temperature in Table 61. This system ran shorter cycles at lower refrigerant levels.

TABLE 61. MAYFAIR 2 TON VCHP CYCLING CHARACTERISTICS IN HEATING MODE

	DAILY AVERAGE OUTDOOR TEMPERATURE (°F)	REFRIGERANT LEVEL			
		50%	65%	80%	100%
Average Cycle Length (Minutes)	45	17.4	-	25.1	26.7
	50	15.4	18.4	22.3	25.0
	55	17.8	16.2	-	20.6
	60	-	16.9	-	21.8
Average Cycles Per Day	45	26.4	-	19.0	20.7
	50	25.0	12.0	18.6	12.8
	55	9.0	6.0	-	9.6
	60	-	1.3	-	1.5

DAILY ENERGY USE

The daily heating energy use regression results for the 2 Ton VCHP are shown in Table 62. Figure 147 displays the monitored and regression predicted daily energy use for each refrigerant level. Figure 148 displays the monitored and regression predicted VCHP daily energy use plotted against daily average outdoor temperature, comparing the modeled results to directly monitored data.

TABLE 62. MAYFAIR 2 TON VCHP DAILY HEATING ENERGY REGRESSION

SYSTEM	VARIABLE	COEFFICIENT	t	95% CONFIDENCE INTERVAL	
2 Ton VCHP	E _{Ref}	0.2354	17.91	0.2086	0.2621
	E _{Ref_R50}	-0.0281	-2.61	-0.0500	-0.0062
	E _{Ref_R65}	-0.0118	-0.41	-0.0707	0.0470
	E _{Ref_R80}	-0.0099	-0.94	-0.0314	0.0116
	Constant	0.0769	0.39	-0.3234	0.4772
	R ²	0.94			
	Daily Standby kWh	0.50			
	Total Heating Season Crankcase Heat kWh	6			

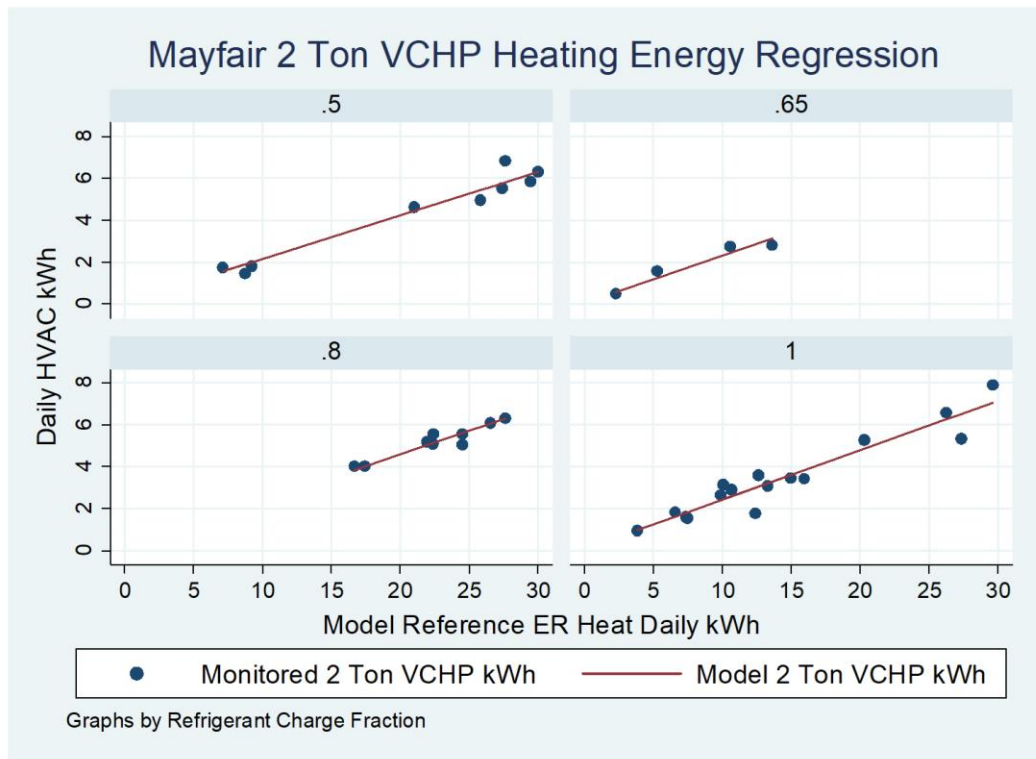


FIGURE 147. MAYFAIR 2 TON VCHP DAILY HEATING ENERGY REGRESSION

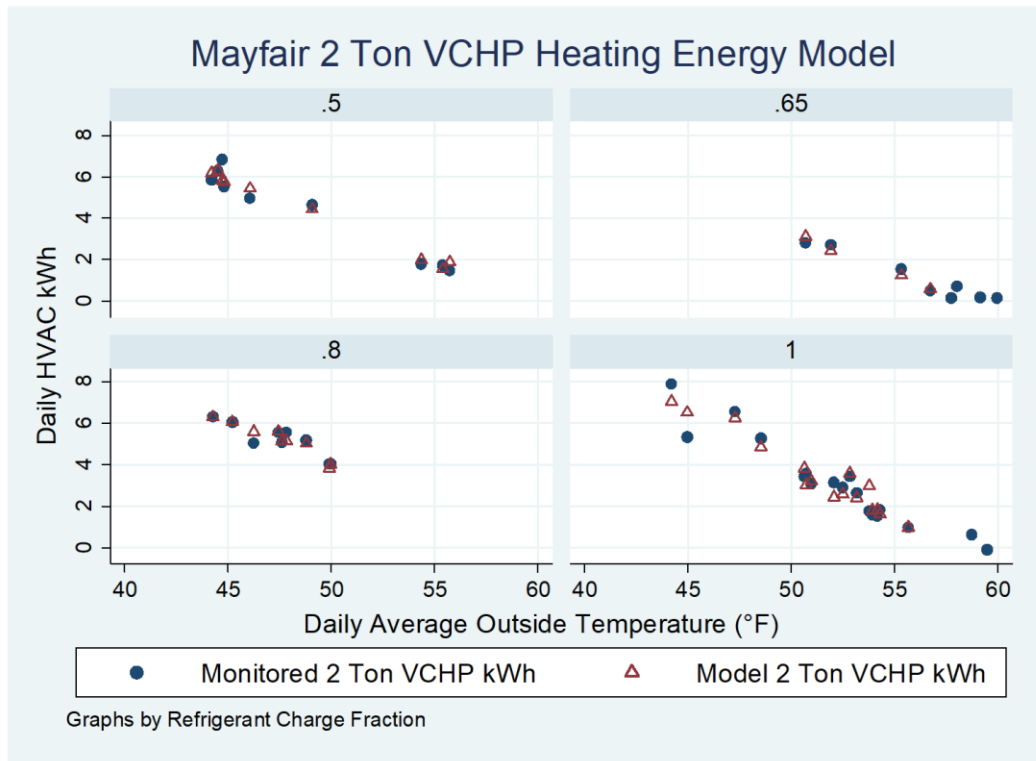


FIGURE 148. MAYFAIR 2 TON VCHP MONITORED AND MODEL PREDICTED DAILY HEATING ENERGY

The regression predicted normalized seasonal energy use estimates are shown in Table 63. The daily energy use analysis shows an efficiency improvement at low refrigerant levels, including at 50% undercharge.

TABLE 63. MAYFAIR 2 TON VCHP NORMALIZED HEATING SEASON ENERGY USE

SYSTEM	REFRIGERANT LEVEL	SEASONAL ENERGY USE (kWh)	SEASONAL ENERGY USE RELATIVE TO CORRECT REFRIGERANT CHARGE	IMPLIED EFFICIENCY RELATIVE TO CORRECT REFRIGERANT CHARGE
2 Ton VCHP	50%	735.8	90%	112%
	65%	785.6	96%	105%
	80%	791.5	96%	104%
	100%	821.8	100%	100%

The unexpected reduction in energy use at lower refrigerant levels appears to be related to the control programming of the 2 ton VCHP unit. Figure 149 and Figure 150 show the unit operating over 5 hours with very similar outdoor conditions at correct refrigerant charge and at 50% refrigerant charge. Input power was approximately 100W higher on the morning with 50% refrigerant charge, and air temperature rise measured between the return and supply plenums was approximately 3 °F higher. Indoor unit power was the same in both cases, indicating

indoor airflow was the same. This suggests that the system was operating at a higher compressor speed and delivering a higher heating capacity when undercharged. At these conditions, the relative increase in temperature rise exceeded the relative increase in input power, meaning that the unit was operating more efficiently and delivering more heat per kW of input power at low refrigerant charge than at correct refrigerant charge.

This system is oversized for the heating load and did not operate at full capacity at any time during testing. The monitored results may differ from efficiency impacts at higher capacity operation.

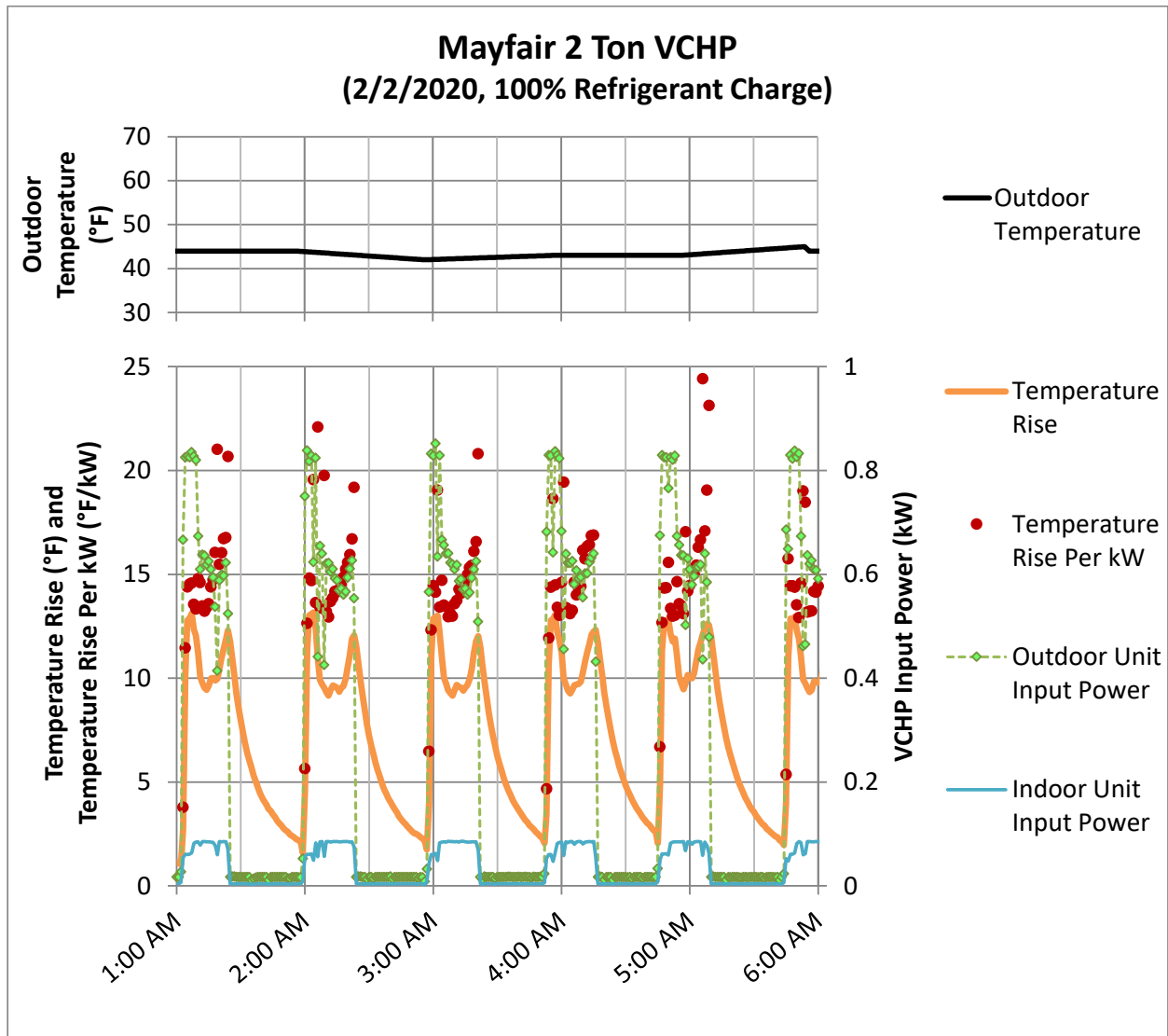


FIGURE 149. MAYFAIR 2 TON VCHP CYCLING AT CORRECT REFRIGERANT CHARGE

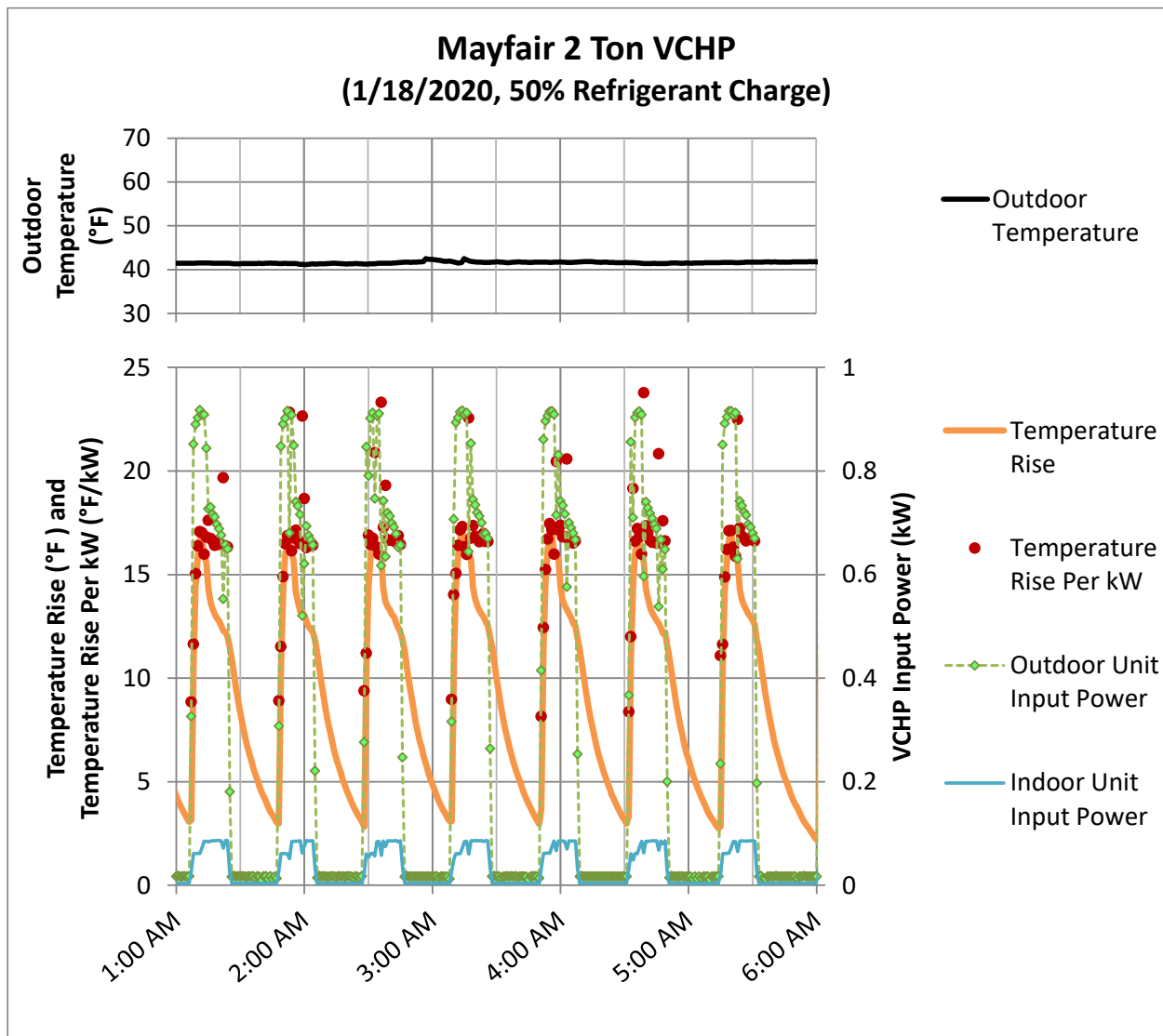


FIGURE 150. MAYFAIR 2 TON VCHP CYCLING AT 50% REFRIGERANT CHARGE

EVALUATIONS

COOLING EFFICIENCY

Seasonal energy use and efficiency results for each system and refrigerant level are shown in Table 64. The values shown are relative to performance at correct refrigerant charge.

The combined seasonal efficiency results are plotted in Figure 151. On average, these VCHP systems are estimated to lose 10% of their cooling efficiency when refrigerant levels are 25% low and 20% of their cooling efficiency when refrigerant levels are 45% low. These are conservative estimates of efficiency and energy impacts since some systems failed to meet the cooling load at low refrigerant levels and would have used more energy if loads had been met.

TABLE 64. IMPACT OF LOW REFRIGERANT CHARGE ON COOLING ENERGY USE AND EFFICIENCY

REFRIGERANT LEVEL	SYSTEM	REFRIGERANT % OF MANUFACTURER SPECIFIED VALUE	NORMALIZED SEASONAL ENERGY USE	NORMALIZED SEASONAL EFFICIENCY
50%	Caleb Ducted VCHP	50%	130%	77%
	Caleb Ductless VCHP	49%	159%	63%
	Grange .75 Ton VCHP	50%	131%	76%
	Grange 1 Ton VCHP	51%	152%	66%
	Mayfair 1.5 Ton VCHP*	49%	126%	79%
	Mayfair 2 Ton VCHP	49%	117%	86%
65%	Caleb Ducted VCHP	64%	117%	85%
	Caleb Ductless VCHP	65%	121%	83%
	Grange .75 Ton VCHP	65%	117%	85%
	Grange 1 Ton VCHP	66%	110%	91%
	Mayfair 1.5 Ton VCHP*	66%	113%	88%
	Mayfair 2 Ton VCHP	66%	111%	90%
80%	Caleb Ducted VCHP	80%	107%	94%
	Caleb Ductless VCHP	80%	106%	94%
	Grange .75 Ton VCHP	80%	110%	91%
	Grange 1 Ton VCHP	80%	112%	90%
	Mayfair 1.5 Ton VCHP	79%	112%	89%
	Mayfair 2 Ton VCHP	80%	109%	91%

* Efficiency impacts of low refrigerant levels are underestimated. The 1.5 Ton VCHP system did not meet cooling loads under these conditions.

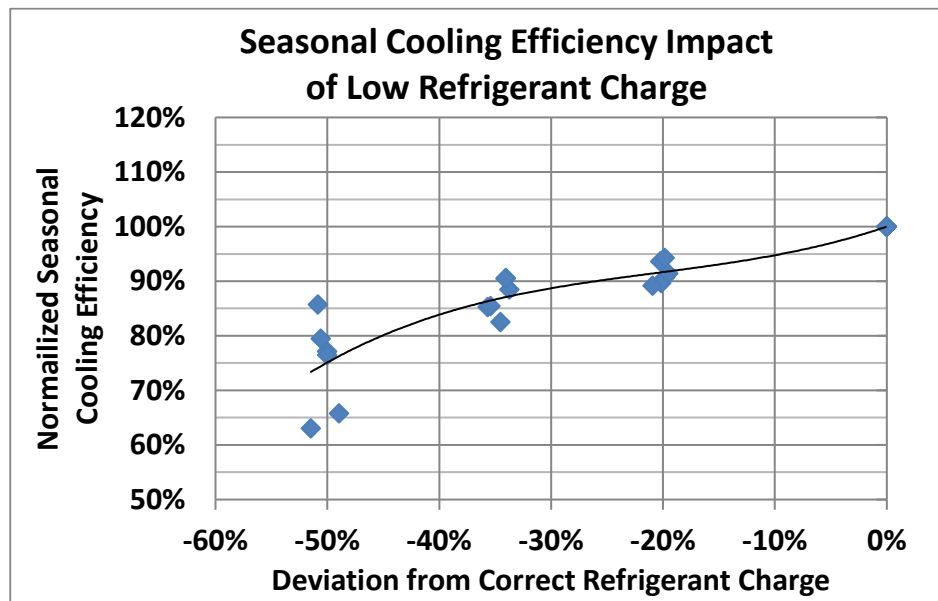


FIGURE 151. SEASONAL COOLING EFFICIENCY IMPACT OF LOW REFRIGERANT CHARGE

HEATING EFFICIENCY

Seasonal energy use and efficiency results for each system and refrigerant level are shown in Table 65. The values shown are relative to performance at correct refrigerant charge. In general, the heating mode impacts of low refrigerant charge were smaller than the cooling mode impacts.

The combined seasonal efficiency results are plotted in Figure 152. On average, these VCHP systems are estimated to lose 11% of their heating efficiency when refrigerant levels are 50% low. The study did not find evidence of significant heating efficiency losses at lower levels of refrigerant undercharge.

The 65% refrigerant charge evaluation occurred at the end of heating season and was affected by warm weather and very low heating loads. The monitored results cannot be confidently extrapolated to colder conditions with higher heating loads. The apparent efficiency gains for most systems during the 65% refrigerant charge test are not representative of performance under typical heating conditions.

Heating efficiency impacts at 50% refrigerant charge ranged from greater than 40% loss for the Caleb ductless VCHP to 12% improved efficiency for the Mayfair 2 ton VCHP. This suggests that different VCHP systems may respond very differently to incorrect refrigerant levels. These differences may be driven not only by physical characteristics of the mechanical components, but also by the onboard control programming.

TABLE 65. IMPACT OF LOW REFRIGERANT CHARGE ON HEATING ENERGY USE AND EFFICIENCY

REFRIGERANT LEVEL	SYSTEM	REFRIGERANT % OF MANUFACTURER SPECIFIED VALUE	NORMALIZED SEASONAL ENERGY USE	NORMALIZED SEASONAL EFFICIENCY
50%	Caleb Ducted VCHP	50%	113%	88%
	Caleb Ductless VCHP	50%	173%	58%
	Grange 0.75 Ton VCHP	48%	110%	91%
	Grange 1 Ton VCHP	51%	111%	90%
	Mayfair 1.5 Ton VCHP	51%	109%	92%
	Mayfair 2 Ton VCHP	50%	90%	112%
65%*	Caleb Ducted VCHP	65%	90%	111%
	Caleb Ductless VCHP	66%	126%	80%
	Grange 0.75 Ton VCHP	65%	85%	118%
	Grange 1 Ton VCHP	65%	85%	118%
	Mayfair 1.5 Ton VCHP	65%	90%	111%
	Mayfair 2 Ton VCHP	64%	96%	105%
80%	Caleb Ducted VCHP	80%	103%	97%
	Caleb Ductless VCHP	80%	107%	93%
	Grange 0.75 Ton VCHP	80%	102%	98%
	Grange 1 Ton VCHP	80%	104%	96%
	Mayfair 1.5 Ton VCHP	81%	101%	99%
	Mayfair 2 Ton VCHP	80%	96%	104%

* The 65% monitoring period was affected by mild weather and very low heating loads. The apparent efficiency gains observed at most sites are not representative of performance at typical heating conditions.

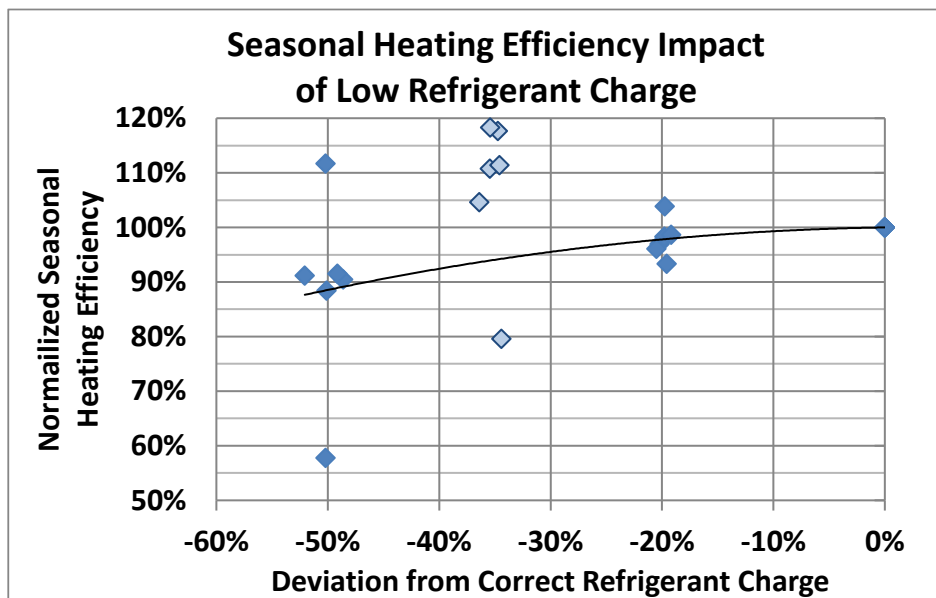


FIGURE 152. SEASONAL HEATING EFFICIENCY IMPACT OF LOW REFRIGERANT CHARGE

There are two important factors to consider when interpreting the heating results as they may apply to climate regions that are colder than Stockton, CA:

- 1) All of the VCHP systems were oversized by more than 100% relative to the heating loads in the houses. Four of the six systems were oversized by 200% or more. As a result, they did not operate at higher capacity/compressor speeds.
- 2) Because the VCHP systems were very oversized, they were able to meet heating loads even at the lowest refrigerant levels.

Heat pump oversizing relative to heating loads is not unusual in areas of California with hot summer temperatures and mild winters. Heat pumps installed in colder climates are likely to be sized closer to or even smaller than the heating loads on cold days. Efficiency losses at full compressor speed may exceed those documented in this study. It is also likely that heating capacity losses at low refrigerant levels would increase the use of supplemental heat sources in cases where the heat pump is sized closer to the heating load.

OTHER OBSERVATIONS

On average, the monitored cooling and heating efficiency losses at reduced refrigerant levels are similar to those that have been documented for single speed heat pumps with a thermostatic expansion valve in prior laboratory studies (Davis 2001, Kruse 2006, Domanski 2014).

Low refrigerant levels increased peak demand on summer evenings for four of the six VCHP systems monitored. At the lowest refrigerant levels peak demand increased by as much as 100%. This project applied a constant thermostat setpoint throughout the cooling season. Peak demand impacts resulting from low refrigerant charge may be larger than the monitored results if a daytime set-up and evening set-down schedule is used.

None of the VCHP systems evaluated in this experiment provide a method of test to verify refrigerant levels are correct without fully evacuating the system and weighing the refrigerant.

The monitored data does not indicate that occupants would be aware that there was any problem with the VCHP for nearly all of the systems and refrigerant levels tested. There was only one case (Caleb Ducted VCHP at 50% refrigerant charge during cooling season) where the VCHP system was observed to malfunction in ways that would be noticeable to the occupant (failed to operate or failed to deliver any cooling on the 2nd floor) on some days as a result of low refrigerant charge. In all other cases the VCHP systems continued to provide heating and cooling at a level that most occupants are likely to perceive as within the normal range of operation.

If these VCHP systems are installed with incorrect refrigerant levels, it is likely that the monitored efficiency losses would persist indefinitely. If leaks or other problems cause refrigerant levels to become incorrect after installation, it is unlikely that these systems will ever be restored to the correct refrigerant levels. The problem is not visible to occupants. There is no practical test that HVAC contractors can use to check refrigerant levels during post-installation commissioning or subsequent maintenance visits. Fully evacuating and weighing the refrigerant is very time consuming and costly, and is unlikely to occur during residential HVAC maintenance

work except in the case of major repairs such as replacement of the compressor or outdoor unit heat exchanger.

All of the VCHP systems tested were equipped with flare type refrigerant line connections, which are currently typical for residential mini and multi split systems. Flare connections have been documented to be more likely to leak at the time of installation, and to develop leaks after installation, than brazed or other connection types (Elbel 2018). The monitored results indicate that if a refrigerant leak occurs, VCHP systems are likely to continue operating until refrigerant levels become very low. Five of the six systems tested would lose more than half of their refrigerant before an occupant is likely to notice the problem. In addition to efficiency losses, there are also significant greenhouse gas impacts associated with refrigerant losses of this magnitude.

RECOMMENDATIONS

The study documented substantial cooling mode efficiency losses and the potential for heating mode efficiency losses when the VCHP systems were operated at reduced refrigerant levels. It is recommended that:

- California Title 24 should continue to apply refrigerant charge verification requirements for VCHP systems.
- California Title 24 should continue to apply efficiency loss assumptions to VCHP systems with unverified refrigerant charge. The existing assumption of 10% efficiency loss for central air conditioners and heat pumps is appropriate for VCHP systems because the efficiency losses documented in this study are similar to the losses that would be expected to occur on a standard heat pump system with a thermostatic expansion valve.
- VCHP manufacturers should be encouraged to develop refrigerant charge methods of test that enable equipment installers and maintenance technicians to ensure field installed VCHP systems contain the correct amount of refrigerant. Providing a credit in Title 24 would be one way to encourage this effort. It would be reasonable to assume degraded lifetime efficiency for equipment that lacks methods of test to facilitate ongoing maintenance at correct refrigerant levels. Methods of test must be feasible and practical for residential HVAC contractors. Examples of practical tests include the superheat and subcooling tests that have long been standard for conventional heat pumps. Removing all of the refrigerant and weighing it is not a practical maintenance procedure.
- VCHP manufacturers should be encouraged to develop onboard systems to detect incorrect refrigerant levels or leaks and alert occupants and the HVAC contractor that there is a problem. Providing a credit in Title 24 would be one way to encourage this effort.
- VCHP manufacturers should be encouraged to adopt refrigerant line connections that are less prone to leakage than flare connections. At present, the installation instructions for nearly all residential mini and multi split type systems specify flare connections.

- Energy efficiency programs that install VCHP systems should include the following components to promote superior technologies and installation practices:
 - Incentivize systems that provide effective refrigerant charge methods of test and/or onboard refrigerant fault detection.
 - Encourage the adoption of refrigerant line connections such as press fittings that are demonstrated to be less prone to leakage than flare connections.
 - Enforce procedures to ensure refrigerant levels are properly adjusted and that all refrigerant line connections are tested and verified to not leak.
 - Include rigorous technician training and certification requirements. At minimum, training should include:
 - Evacuation and charging procedures
 - Refrigerant adjustment to compensate for lineset length
 - Correct installation of refrigerant line connections, including flare connections and options such as press fittings that are demonstrated to be less prone to leakage
 - Refrigerant charge verification methods.

REFERENCES

- ACCA. (2016). Manual J - Residential Load Calculation. Air Conditioning Contractors of America
- AHRI. (2017). Standard 210/240 Performance Rating of Unitary Air-conditioning & Air-source Heat Pump Equipment. America Air-Conditioning, Heating and Refrigeration Institute
- CEC. (2019). Residential Alternative Calculation Method Reference Manual. CEC-400-2019-005-CMF. California Energy Commission
- Davis R. (April 2001). Influence of Expansion Device and Refrigerant Charge on the Performance of a Residential Split System Air Conditioner using R-410A Refrigerant. PG&E Technical and Ecological Services Performance Testing and Analysis Unit
- Domanski, P., Henderson, H., Payne, V. (September 2014). Sensitivity Analysis of Installation Faults on Heat Pump Performance. NIST Technical Note 1848. National Institute of Standards and Technology
- Elbel, S., Lawrence, N., Raj, S. (2018). Leakage Rate Measurement and Durability Testing of Field-Made Mechanical Joints for Systems with Flammable Refrigerants (ASHRAE RP-1808). International Refrigeration and Air Conditioning Conference. Paper 1940
- Kruse, E., Palmiter, L. (2006). Measured Effect of Air Flow and Refrigerant Charge on Heat Pump Performance in Heating Mode. ACEEE Summer Study on Energy Efficiency in Buildings. American Council for an Energy Efficient Economy
- Pigg, S. (May 2008). Central Air Conditioning in Wisconsin, a Compilation of Recent Field Research. ECW 241-1. Energy Center of Wisconsin
- Proctor, J., Downey, T. (2002). What Can 13,000 Air Conditioners Tell Us? ACEEE Summer Study on Energy Efficiency in Buildings. American Council for an Energy Efficient Economy
- Wilcox, B. A., Proctor, J., Chitwood, R. (November 2018). Central Valley Research Homes Project. CEC-500-2018-033 California Energy Commission
- Wilcox, B. A., Conant, A. and Chitwood, R. (September 2016). Central Valley Research Homes – Variable Compressor Speed Heat Pumps. ET Project Number ET14PGE8761. Pacific Gas & Electric.
- Wilcox, B. A., Conant, A. and Chitwood, R. (May 2018). Central Valley Research Homes – Variable Compressor Speed Heat Pumps, Evaluation of Ducted and Ductless Configurations 2016-2017. ET Project Number PG&E 2018_3. Pacific Gas & Electric.
- Wilcox, B. A., Conant, A. and Chitwood, R. (May 2019). Central Valley Research Homes – Variable Compressor Speed Heat Pumps, Evaluation of Sizing and Controls Settings 2017-2018. ET Project Number PGE 2019_1. Pacific Gas & Electric.

APPENDIX A. ADJUSTMENT FOR TEMPERATURE DIFFERENCE AT SYSTEM CHANGEOVER

COOLING SEASON

To correct for energy impacts of indoor temperature differences at system changeover during cooling season, energy use between midnight and 6AM was modeled for the 2nd and 3rd days each system operated. The modeled early morning energy use was then applied to the 1st day the system operated following system changeover. This process was performed separately for each refrigerant level test period for each HVAC system.

This approach is based on the assumption that morning energy use on days 2 and 3 of the cycle is representative of what would be expected if the system was operating continuously every day. Therefore, replacing the day 1 midnight to 6AM energy use with the modeled amount produces a day 1 consistent with days 2 and 3, and representative of typical operation for the test scenario. For consistency, the correction was applied to all HVAC systems and all refrigerant charge scenarios even if there was no obvious difference in indoor temperature at system changeover.

The model was developed by regression of energy use against three factors related to cooling loads between midnight and 6AM:

- T_1 : Average outdoor temperature from midnight to 6AM – this factor represents current conditions during the period being modeled.
- T_2 : Average outdoor temperature from 6PM to midnight the preceding day – this factor represents load effects from the immediately preceding time period.
- T_3 : Daily high temperature of the preceding day – this factor represents load effects from the preceding afternoon, some of which may carry over into the current day if the HVAC system failed to meet loads during the preceding afternoon.

Table 66 – Table 74 show the regression coefficients for each HVAC system. Figure 153 – Figure 161 plot the uncorrected and corrected daily energy use amounts for each HVAC system.

TABLE 66. CALEB DUCTED VCHP MIDNIGHT TO 6AM COOLING ENERGY USE REGRESSIONS

SYSTEM	REFRIGERANT LEVEL	T ₁	T ₂	T ₃	C	R ²
Ducted VCHP	50%	0.0947	0.0188	0.0414	-9.82	1.00
	65%	0.0674	0.0619	0.0431	-10.74	0.99
	80%	0.0575	0.0510	0.0117	-6.61	0.99
	100%	0.0184	0.1156	0.0213	-9.49	0.98

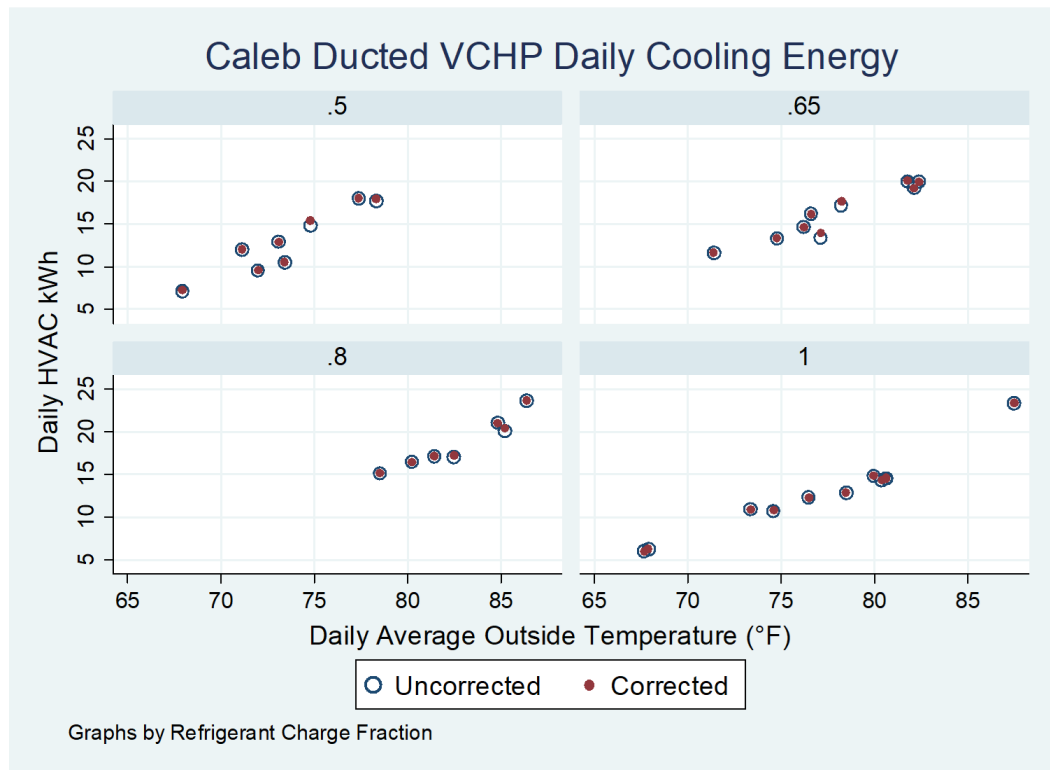


FIGURE 153. CALEB DUCTED VCHP DAILY COOLING kWh, WITH AND WITHOUT CORRECTION FOR EARLY MORNING ENERGY USE AT SYSTEM CHANGEOVER

TABLE 67. CALEB DUCTLESS VCHP MIDNIGHT TO 6AM COOLING ENERGY USE REGRESSIONS

SYSTEM	REFRIGERANT LEVEL	T ₁	T ₂	T ₃	C	R ²
Ductless VCHP	50%	-0.0320	0.1635	0.0552	-11.84	0.97
	65%	0.0897	0.0163	-0.0097	-5.79	0.99
	80%	-0.0248	0.1150	0.0000	-4.53	1.00
	100%	0.0151	0.0478	0.0055	-3.79	0.90

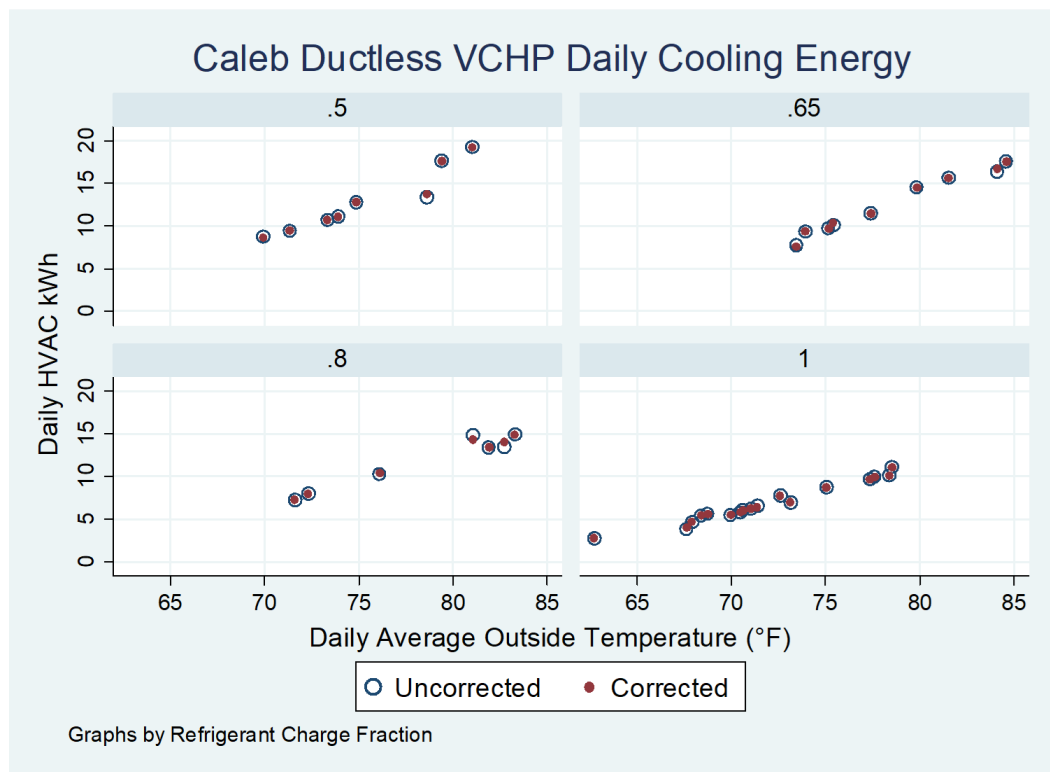


FIGURE 154. CALEB DUCTLESS VCHP DAILY COOLING kWh, WITH AND WITHOUT CORRECTION FOR EARLY MORNING ENERGY USE AT SYSTEM CHANGEOVER

TABLE 68. CALEB REFERENCE HP MIDNIGHT TO 6AM COOLING ENERGY USE REGRESSION

SYSTEM	REFRIGERANT LEVEL	T ₁	T ₂	T ₃	C	R ²
Reference HP	100%	0.0619	0.0408	0.1013	-15.67	0.97

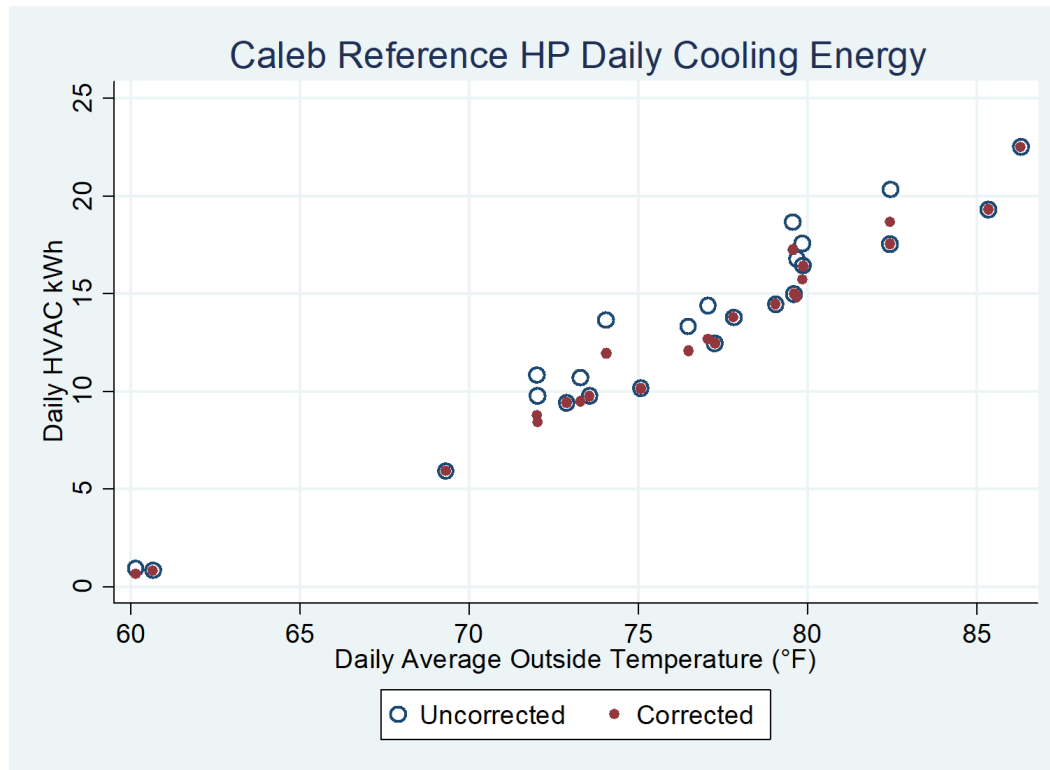


FIGURE 155. CALEB REFERENCE HP DAILY COOLING kWh, WITH AND WITHOUT CORRECTION FOR EARLY MORNING ENERGY USE AT SYSTEM CHANGEOVER

TABLE 69. GRANGE .75 TON VCHP MIDNIGHT TO 6AM COOLING ENERGY USE REGRESSIONS

SYSTEM	REFRIGERANT LEVEL	T ₁	T ₂	T ₃	C	R ²
.75 Ton VCHP	50%	-0.0096	0.0703	0.0105	-4.37	0.95
	65%	-0.0563	0.1044	0.0383	-5.60	0.97
	80%	-0.0051	0.0324	0.0110	-2.21	1.00
	100%	-0.0082	0.0529	0.0053	-2.90	0.97

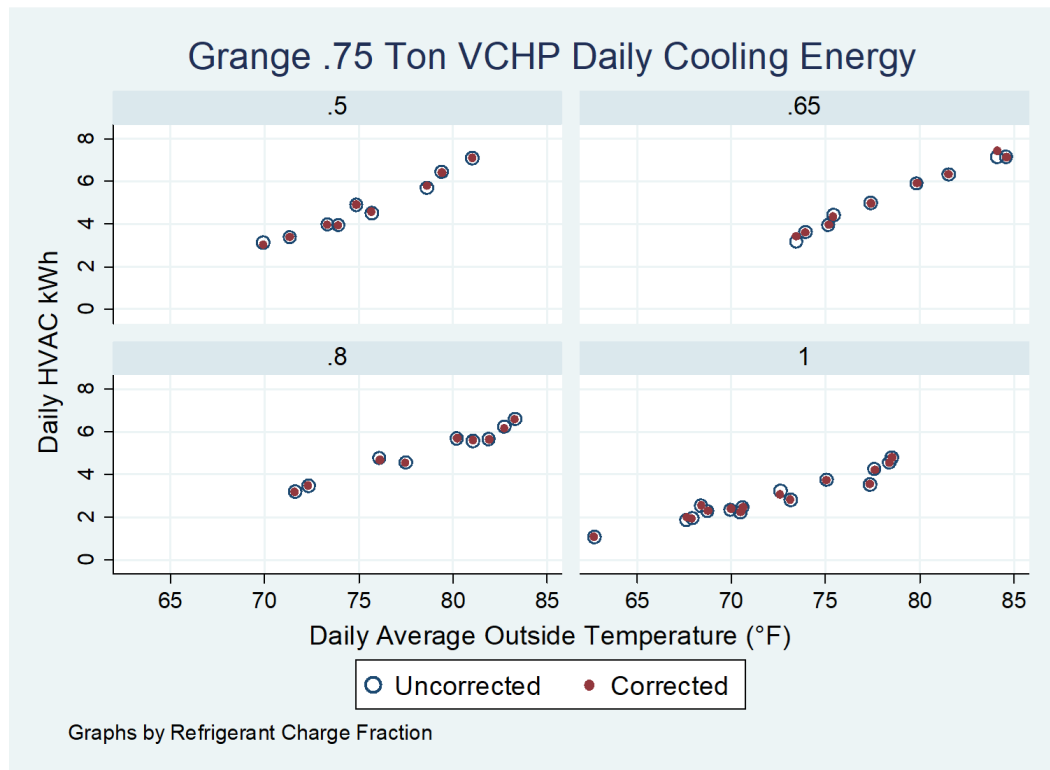


FIGURE 156. GRANGE .75 TON VCHP DAILY COOLING kWh, WITH AND WITHOUT CORRECTION FOR EARLY MORNING ENERGY USE AT SYSTEM CHANGEOVER

TABLE 70. GRANGE 1 TON VCHP MIDNIGHT TO 6AM COOLING ENERGY USE REGRESSIONS

SYSTEM	REFRIGERANT LEVEL	T ₁	T ₂	T ₃	C	R ²
1 Ton VCHP	50%	-0.0597	0.0439	0.0702	-4.09	0.99
	65%	0.0059	0.0187	0.0266	-3.53	0.99
	80%	-0.0095	0.0430	0.0136	-2.78	1.00
	100%	-0.0088	0.0342	0.0186	-2.81	1.00

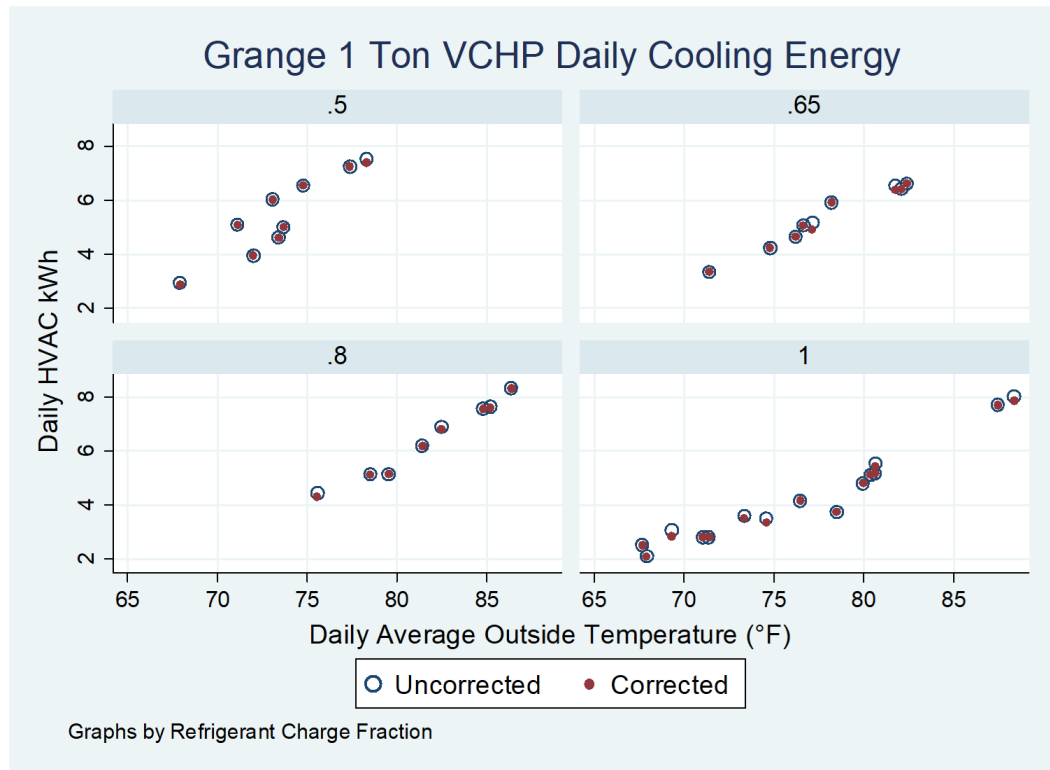


FIGURE 157. GRANGE 1 TON VCHP DAILY COOLING kWh, WITH AND WITHOUT CORRECTION FOR EARLY MORNING ENERGY USE AT SYSTEM CHANGEOVER

TABLE 71. GRANGE REFERENCE HP MIDNIGHT TO 6AM COOLING ENERGY USE REGRESSION

SYSTEM	REFRIGERANT LEVEL	T ₁	T ₂	T ₃	C	R ²
Reference HP	100%	-0.0275	0.0704	0.0619	-8.07	0.91

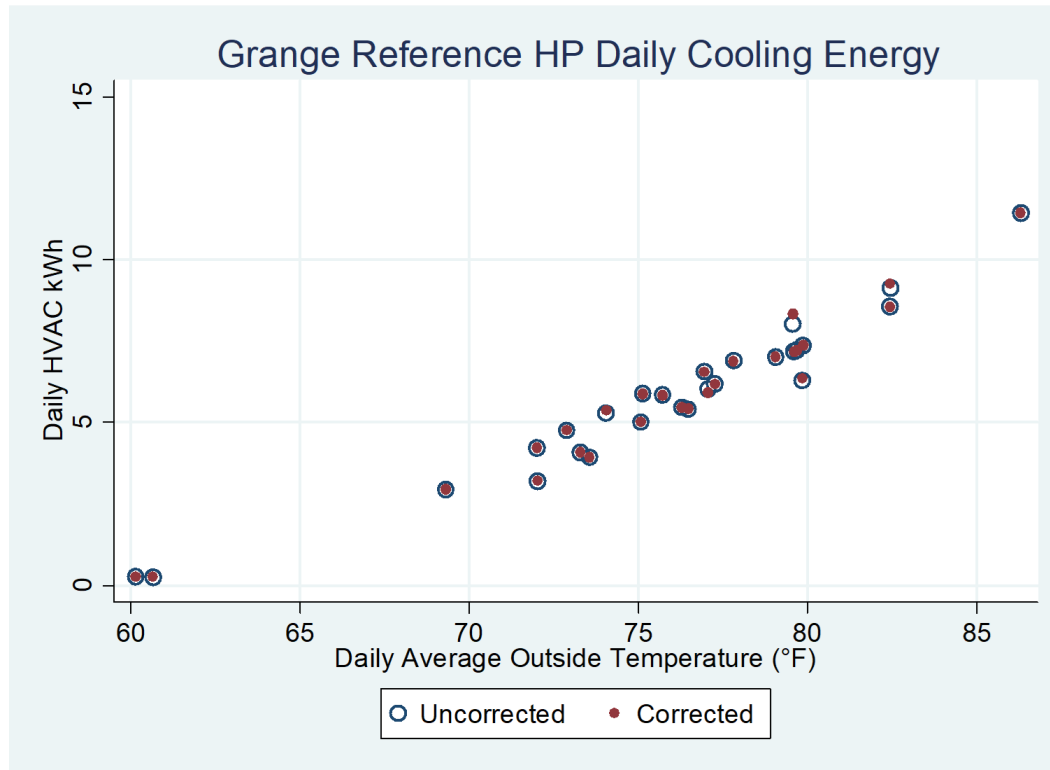


FIGURE 158. GRANGE REFERENCE HP DAILY COOLING kWh, WITH AND WITHOUT CORRECTION FOR EARLY MORNING ENERGY USE AT SYSTEM CHANGEOVER

TABLE 72. MAYFAIR 1.5 TON VCHP MIDNIGHT TO 6AM COOLING ENERGY USE REGRESSIONS

SYSTEM	REFRIGERANT LEVEL	T ₁	T ₂	T ₃	C	R ²
1.5 Ton VCHP	50%	-0.1761	0.1591	0.1991	-13.46	1.00
	65%	0.0133	-0.0045	0.1046	-9.05	0.76
	80%	-0.0790	0.1378	0.0553	-7.08	0.99
	100%	-0.0395	0.0463	0.0542	-4.39	0.94

Larger corrections at low refrigerant levels reflect this system's failure to meet cooling loads during the prior afternoon.

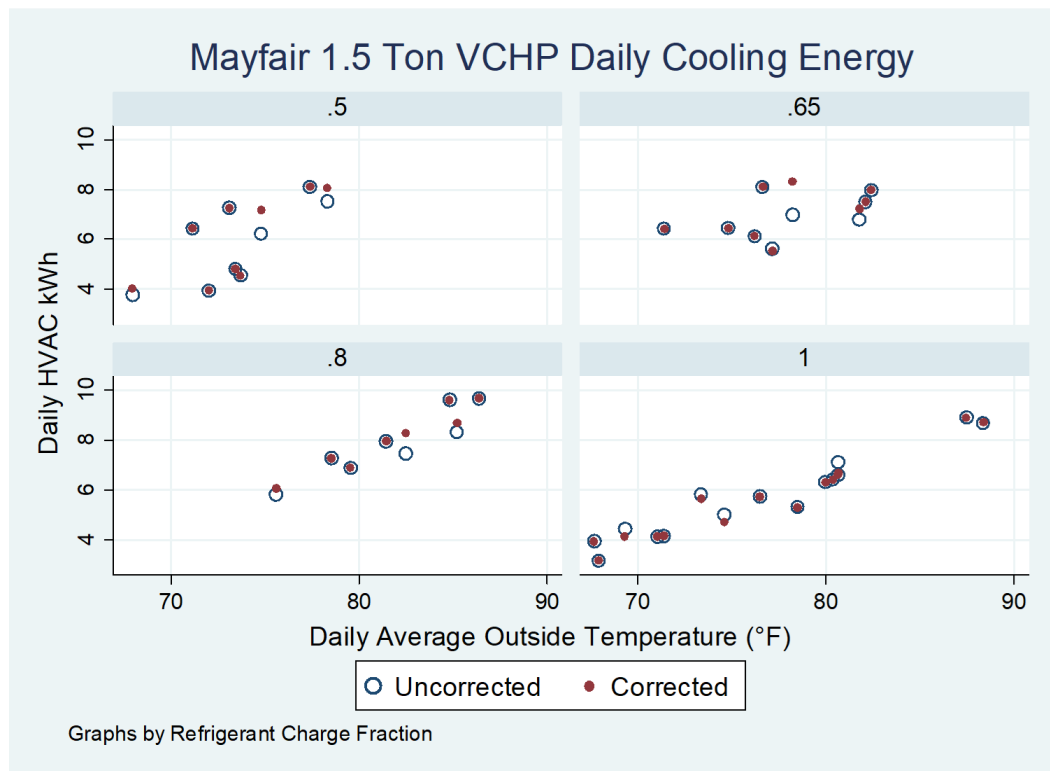


FIGURE 159. MAYFAIR 1.5 TON VCHP DAILY COOLING kWh, WITH AND WITHOUT CORRECTION FOR EARLY MORNING ENERGY USE AT SYSTEM CHANGEOVER

TABLE 73. MAYFAIR 2 TON VCHP MIDNIGHT TO 6AM COOLING ENERGY USE REGRESSIONS

SYSTEM	REFRIGERANT LEVEL	T ₁	T ₂	T ₃	C	R ²
2 Ton VCHP	50%	-0.0024	0.0226	0.0131	-2.29	1.00
	65%	0.0281	-0.0083	0.0199	-3.05	0.98
	80%	0.1096	-0.0490	-0.0373	-1.26	0.96
	100%	-0.0105	0.0326	0.0027	-1.34	0.64

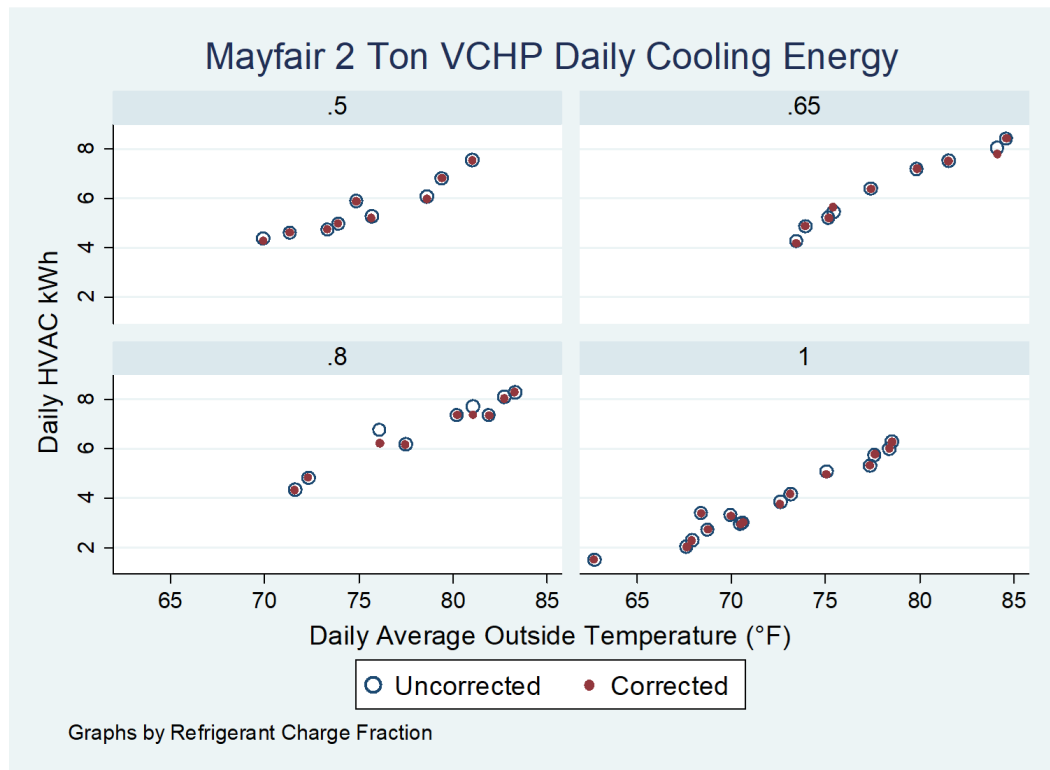


FIGURE 160. MAYFAIR 2 TON VCHP DAILY COOLING kWh, WITH AND WITHOUT CORRECTION FOR EARLY MORNING ENERGY USE AT SYSTEM CHANGEOVER

TABLE 74. MAYFAIR REFERENCE HP MIDNIGHT TO 6AM COOLING ENERGY USE REGRESSION

SYSTEM	REFRIGERANT LEVEL	T ₁	T ₂	T ₃	C	R ²
Reference HP	100%	-0.0207	0.0461	0.0787	-8.40	0.91

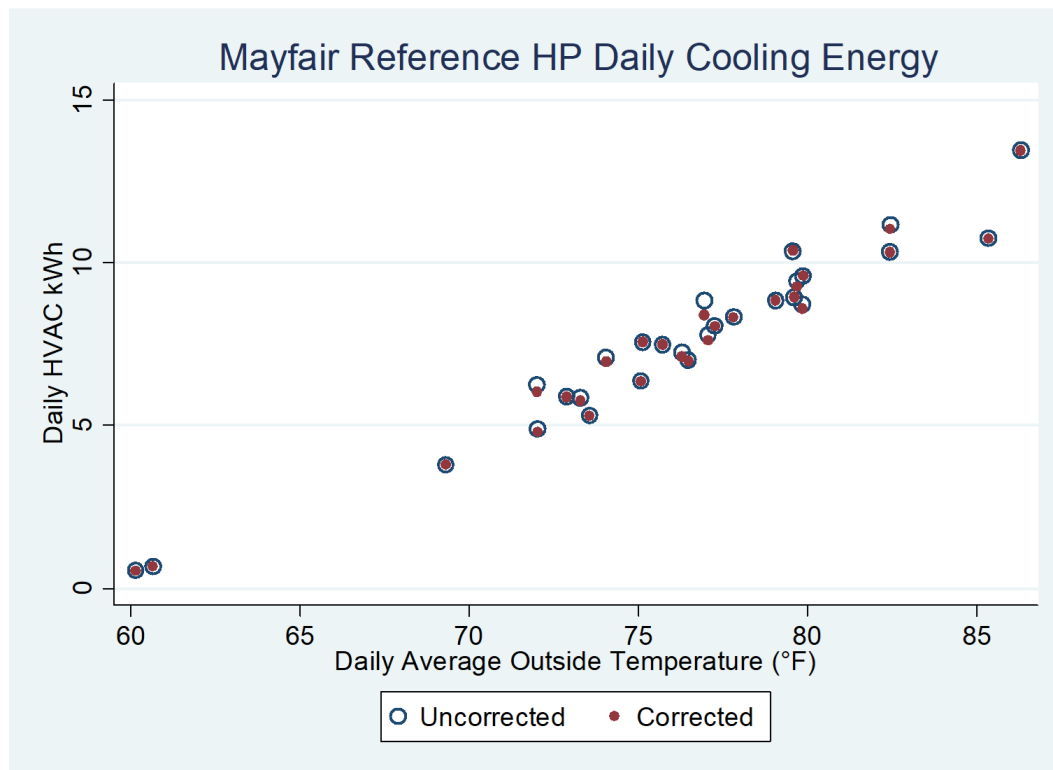


FIGURE 161. MAYFAIR REFERENCE HP DAILY COOLING kWh, WITH AND WITHOUT CORRECTION FOR EARLY MORNING ENERGY USE AT SYSTEM CHANGEOVER

HEATING SEASON

To correct for energy impacts of indoor temperature differences at system changeover during heating season, energy use during the 6 hours following system changeover at 7AM was modeled for the 2nd and 3rd days each system operated. The modeled morning energy use was then applied to the 1st day the system operated following system changeover. This process was performed separately for each refrigerant level test period for each HVAC system.

This approach is based on the assumption that morning energy use on days 2 and 3 of the cycle is representative of what would be expected if the system was operating continuously every day. Therefore, replacing the day 1 morning energy use with the modeled amount produces a day 1 consistent with days 2 and 3, and representative of typical operation for the test scenario. For consistency, the correction was applied to all HVAC systems and all refrigerant charge scenarios even if there was no obvious difference in indoor temperature at system changeover.

The model was developed by regression of morning heating energy use against two factors related to morning heating loads:

- T₁: Average outdoor temperature during the 6 hours prior to 7AM.
- T₂: Average outdoor temperature during the 6 hours following 7AM.

Table 75 - Table 83 show the regression coefficients and the average amount of correction to morning energy use for each HVAC system. Figure 162 - Figure 170 plot the uncorrected and corrected daily energy use amounts for each HVAC system.

TABLE 75. CALEB DUCTED VCHP MORNING HEATING ENERGY USE REGRESSIONS

SYSTEM	REFRIGERANT LEVEL	T ₁	T ₂	C	R ²
Ducted VCHP	50%	0.1036	-0.4133	18.1505	0.90
	65%	-0.0700	0.0091	3.6341	0.61
	80%	-0.0871	-0.0649	9.4454	0.56
	100%	0.0032	-0.1804	10.9699	0.89

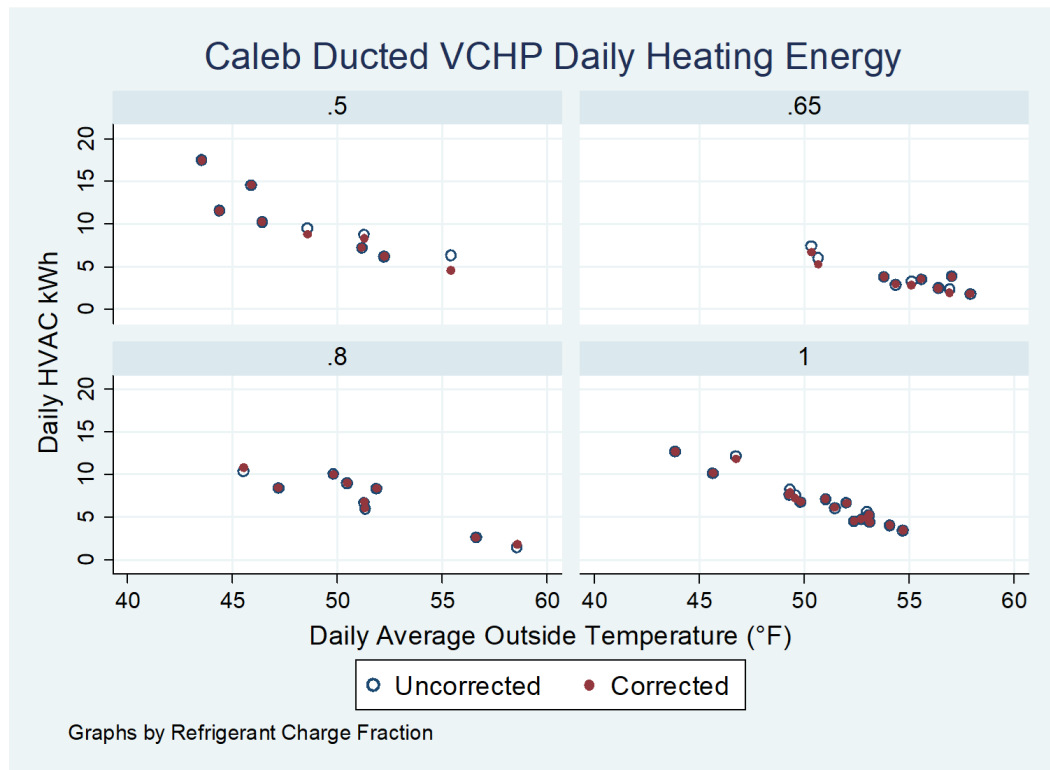


FIGURE 162. CALEB DUCTED VCHP DAILY HEATING kWh, WITH AND WITHOUT CORRECTION FOR MORNING ENERGY USE AT SYSTEM CHANGEOVER

TABLE 76. CALEB DUCTLESS VCHP MORNING ENERGY USE REGRESSIONS

SYSTEM	REFRIGERANT LEVEL	T ₁	T ₂	C	R ²
Ductless VCHP	50%	0.1275	-0.4705	22.5670	0.99
	65%	-0.0900	-0.2420	19.7999	0.98
	80%	-0.0442	-0.0794	9.7077	0.35
	100%	-0.0040	-0.2350	14.9833	0.89

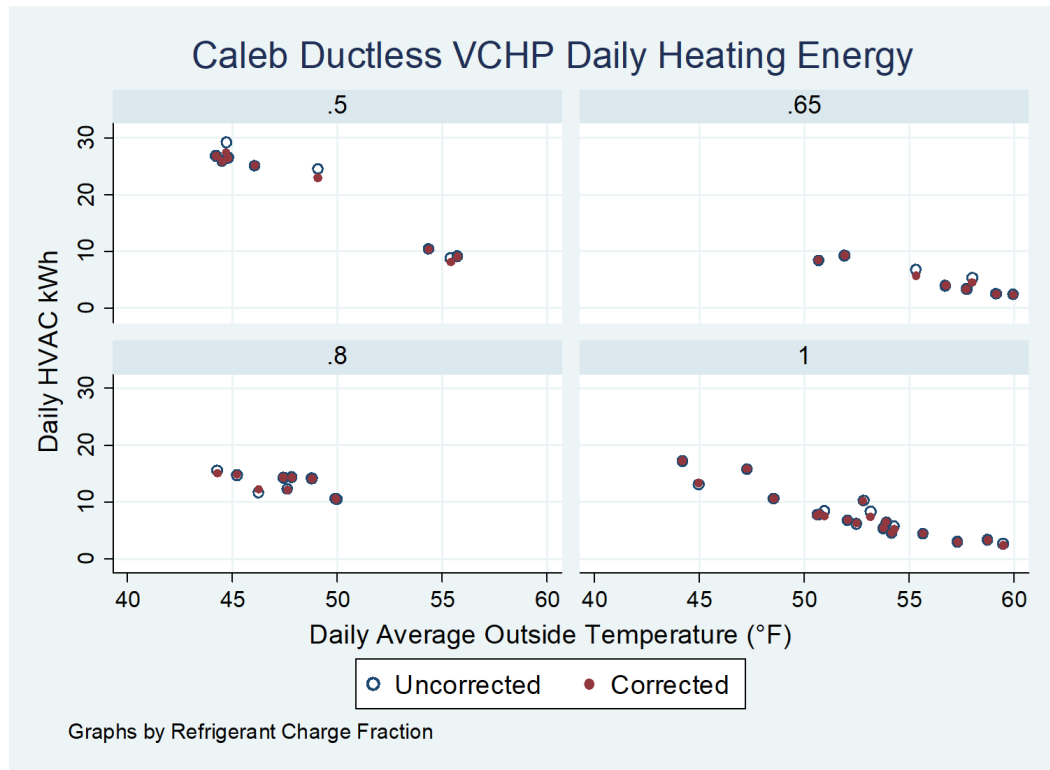


FIGURE 163. CALEB DUCTLESS VCHP DAILY HEATING kWh, WITH AND WITHOUT CORRECTION FOR MORNING ENERGY USE AT SYSTEM CHANGEOVER

TABLE 77. CALEB REFERENCE HP MORNING ENERGY USE REGRESSION

SYSTEM	REFRIGERANT LEVEL	T ₁	T ₂	C	R ²
Reference HP	100%	-0.0691	-0.6182	41.7958	0.91

Larger adjustments reflect that electric resistance heat was preceded by the ductless VCHP system which overheated parts of the house on many mornings.

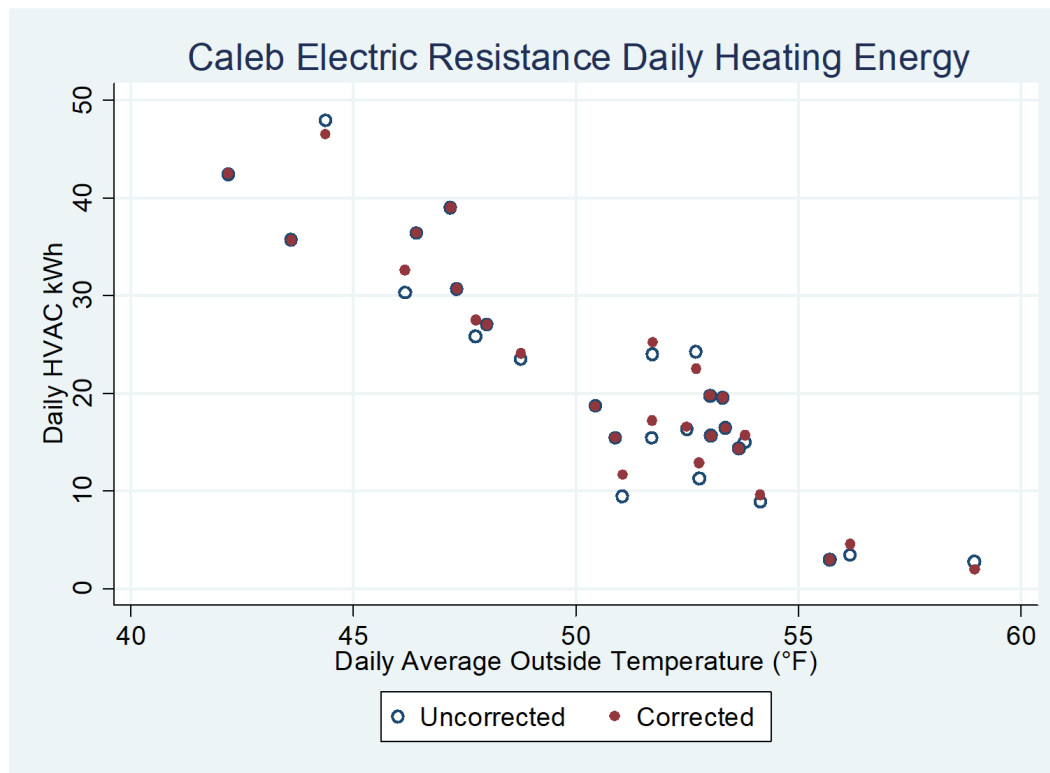


FIGURE 164. CALEB ELECTRIC RESISTANCE HEAT kWh, WITH AND WITHOUT CORRECTION FOR MORNING ENERGY USE AT SYSTEM CHANGEOVER

TABLE 78. GRANGE .75 TON VCHP MORNING ENERGY USE REGRESSIONS

SYSTEM	REFRIGERANT LEVEL	T ₁	T ₂	C	R ²
.75 Ton VCHP	50%	-0.0728	0.0171	3.80	1.00
	65%	0.0163	-0.0671	3.85	0.82
	80%	-0.0239	-0.0269	3.64	0.79
	100%	-0.0203	-0.0479	4.49	0.86

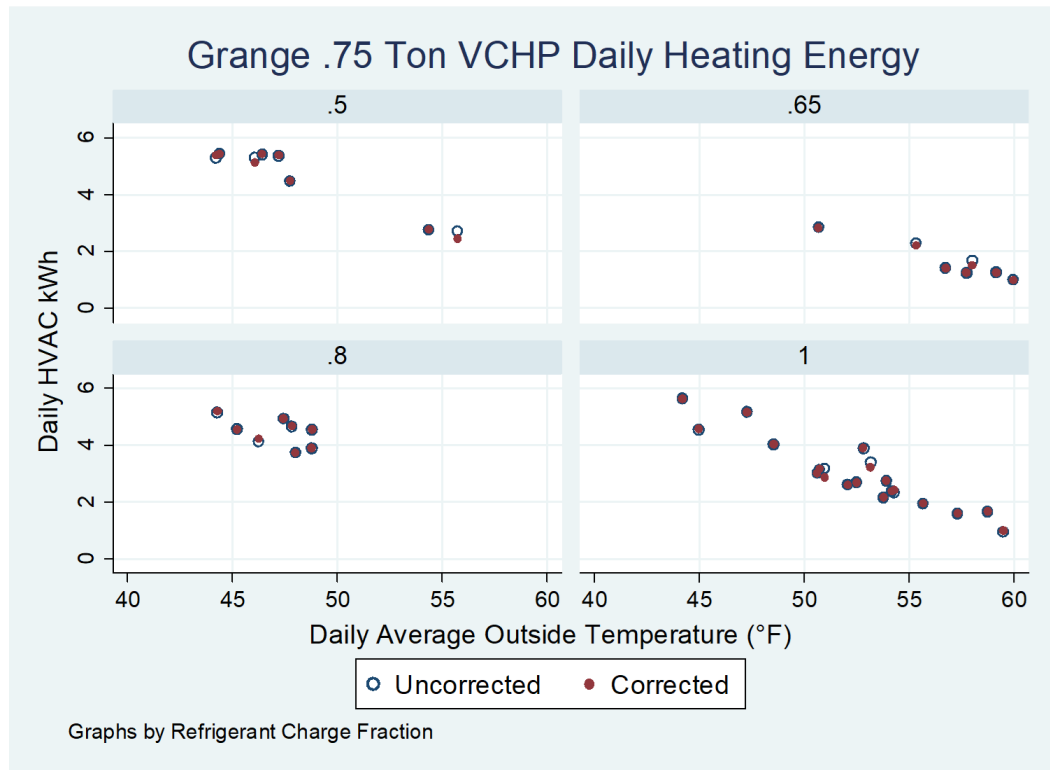


FIGURE 165. GRANGE .75 TON VCHP DAILY HEATING kWh, WITH AND WITHOUT CORRECTION FOR MORNING ENERGY USE AT SYSTEM CHANGEOVER

TABLE 79. GRANGE 1 TON VCHP MORNING ENERGY USE REGRESSIONS

SYSTEM	REFRIGERANT LEVEL	T ₁	T ₂	C	R ²
1 Ton VCHP	50%	0.0480	-0.0333	0.80	0.87
	65%	-0.0347	-0.0315	4.16	0.88
	80%	-0.0064	-0.0653	4.80	0.81
	100%	-0.0103	-0.0236	2.76	0.79

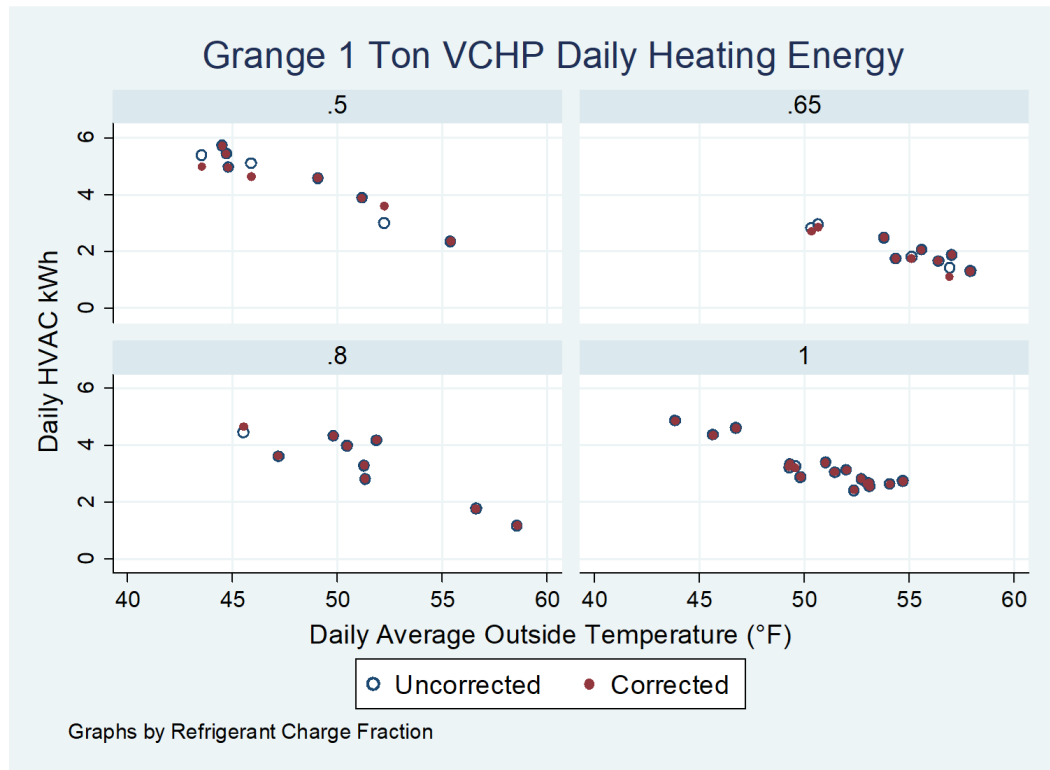


FIGURE 166. GRANGE 1 TON VCHP DAILY HEATING kWh, WITH AND WITHOUT CORRECTION FOR MORNING ENERGY USE AT SYSTEM CHANGEOVER

TABLE 80. GRANGE REFERENCE HP MORNING ENERGY USE REGRESSION

SYSTEM	REFRIGERANT LEVEL	T ₁	T ₂	C	R ²
Reference HP	100%	-0.1037	-0.3033	24.77	0.96

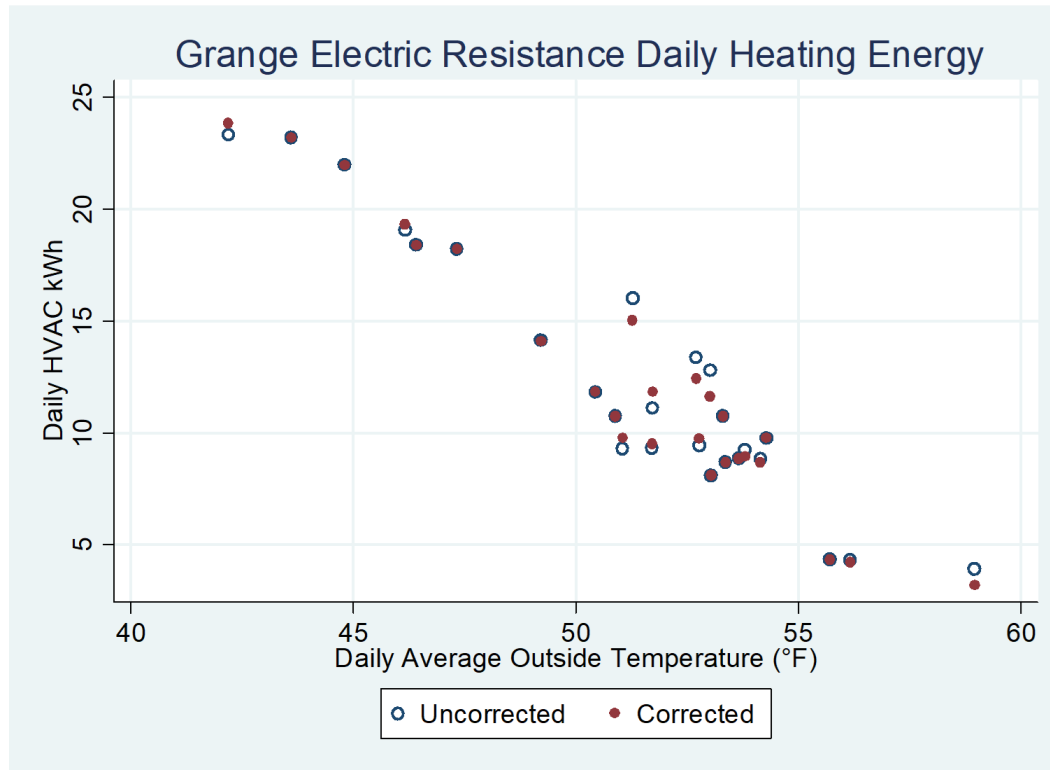


FIGURE 167. GRANGE ELECTRIC RESISTANCE HEAT kWh, WITH AND WITHOUT CORRECTION FOR MORNING ENERGY USE AT SYSTEM CHANGEOVER

TABLE 81. MAYFAIR 1.5 TON VCHP MORNING ENERGY USE REGRESSIONS

SYSTEM	REFRIGERANT LEVEL	T ₁	T ₂	C	R ²
1.5 Ton VCHP	50%	-0.0131	-0.1183	7.84	0.87
	65%	-0.0250	-0.0212	2.91	0.81
	80%	-0.0902	0.0332	3.65	0.85
	100%	0.0529	-0.1544	6.62	0.80

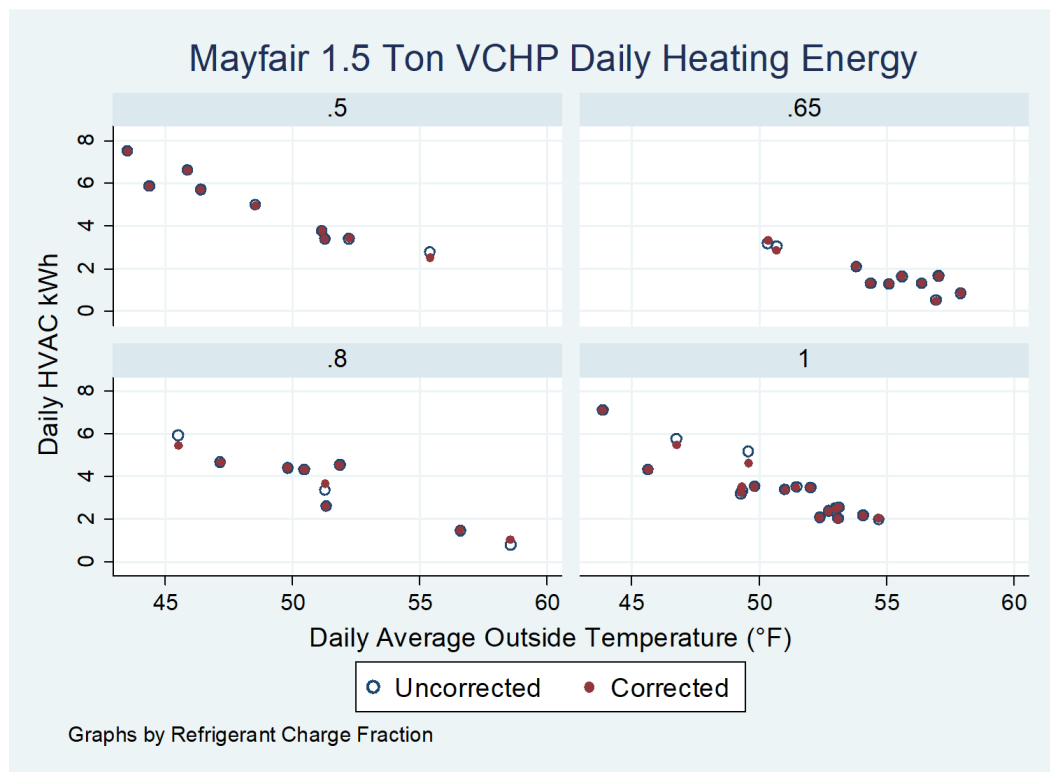


FIGURE 168. MAYFAIR 1.5 TON VCHP DAILY HEATING kWh, WITH AND WITHOUT CORRECTION FOR MORNING ENERGY USE AT SYSTEM CHANGEOVER

TABLE 82. MAYFAIR 2 TON VCHP MORNING ENERGY USE REGRESSIONS

SYSTEM	REFRIGERANT LEVEL	T ₁	T ₂	C	R ²
2 Ton VCHP	50%	-0.0664	-0.0477	6.88	0.99
	65%	-0.0218	-0.0753	5.85	0.97
	80%	-0.0074	-0.0911	6.39	0.77
	100%	-0.0184	-0.1231	8.52	0.96

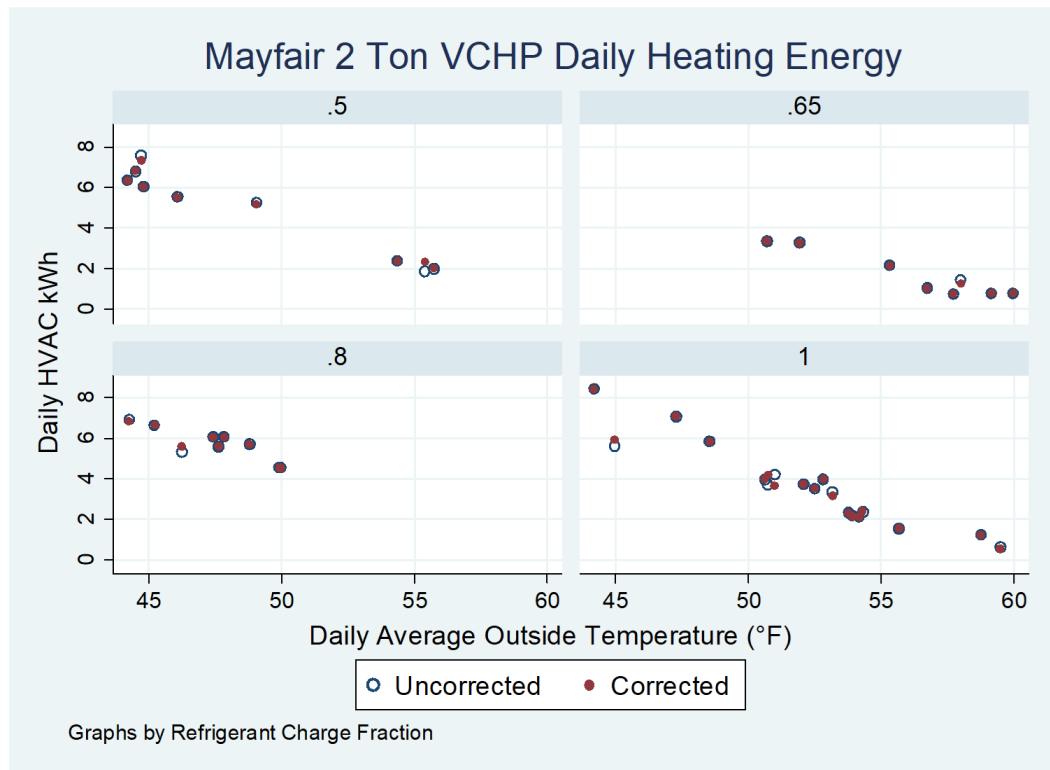


FIGURE 169. MAYFAIR 2 TON VCHP DAILY HEATING kWh, WITH AND WITHOUT CORRECTION FOR MORNING ENERGY USE AT SYSTEM CHANGEOVER

TABLE 83. MAYFAIR REFERENCE HP MORNING ENERGY USE REGRESSION

SYSTEM	REFRIGERANT LEVEL	T ₁	T ₂	C	R ²
Reference HP	100%	-0.0797	-0.4320	30.92	0.94

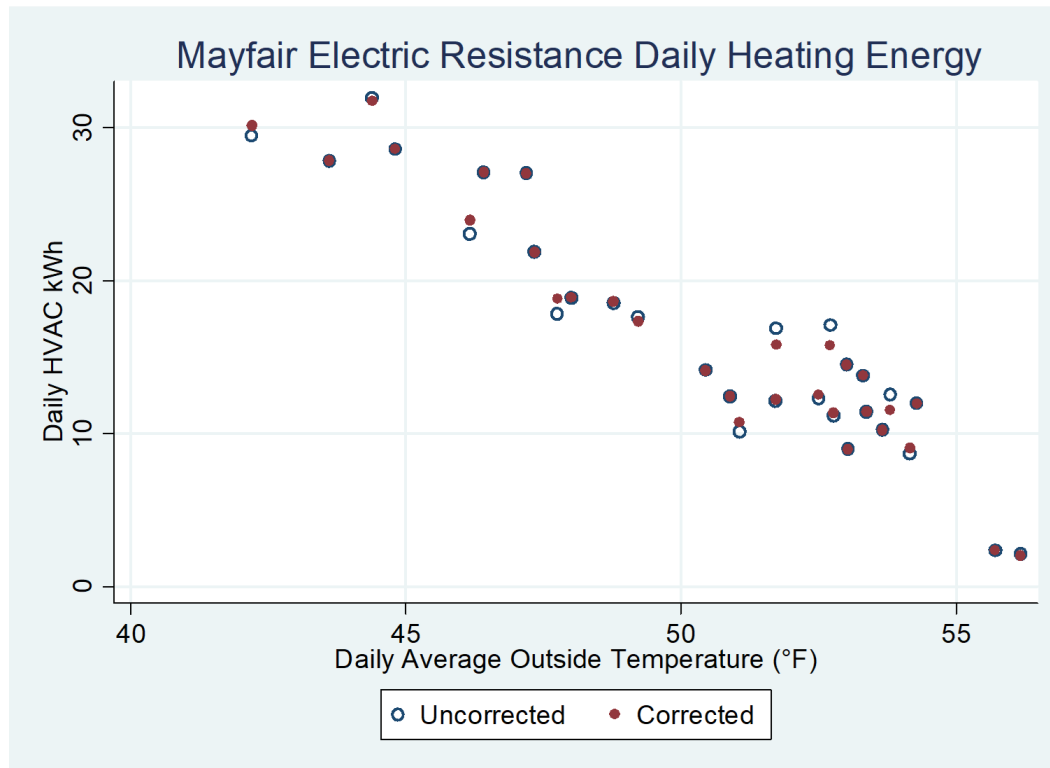


FIGURE 170. MAYFAIR ELECTRIC RESISTANCE HEAT kWh, WITH AND WITHOUT CORRECTION FOR MORNING ENERGY USE AT SYSTEM CHANGEOVER

APPENDIX B. TEMPERATURE DEPENDENT STANDBY ENERGY

Crankcase heat and other temperature dependent standby energy use was only observed in the Mayfair VCHP units.

Figure 171 and Figure 172 show increased standby energy use at low ambient conditions for the Mayfair VCHP units.

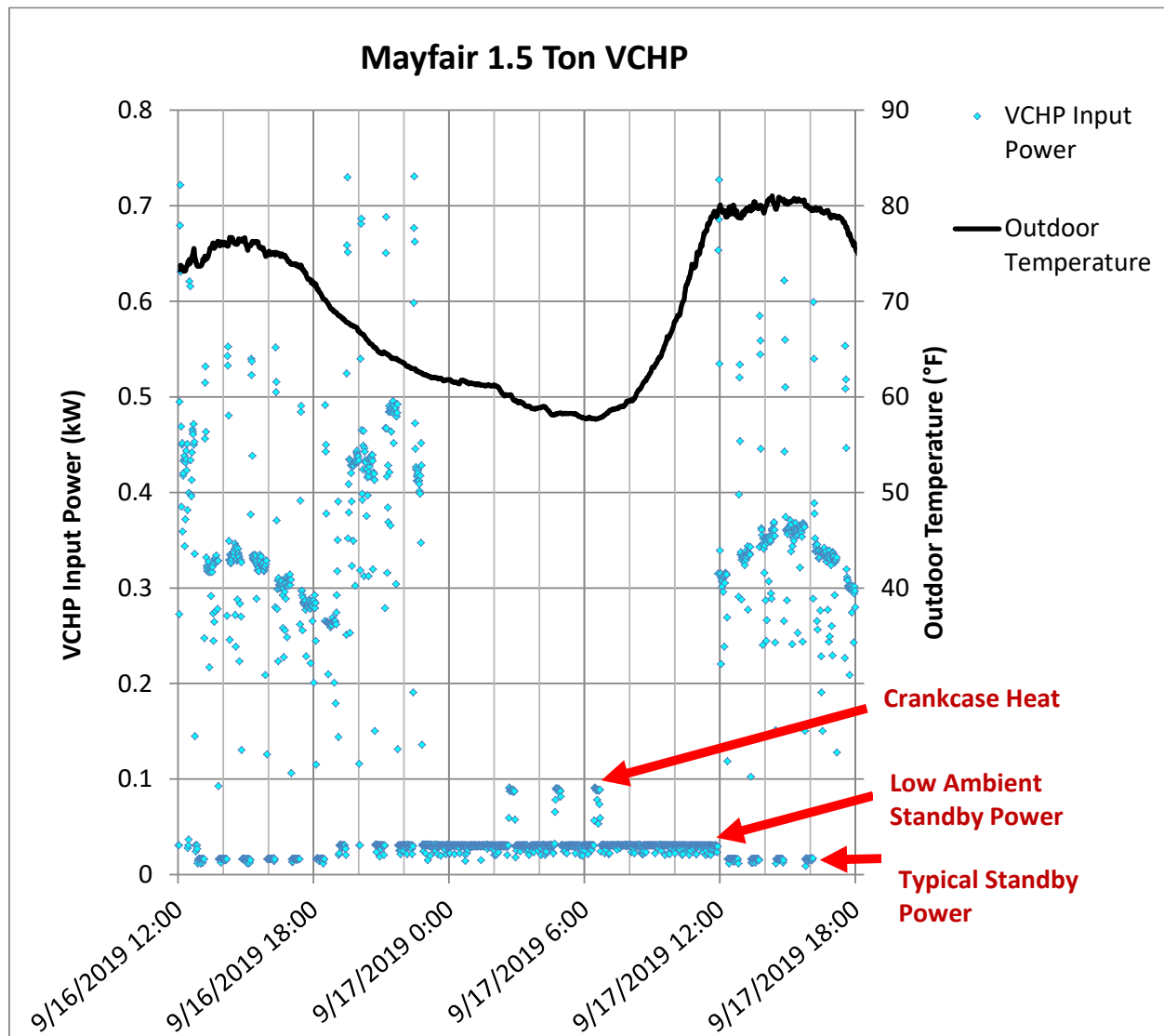


FIGURE 171. MAYFAIR 1.5 TON VCHP TEMPERATURE DEPENDENT STANDBY ENERGY

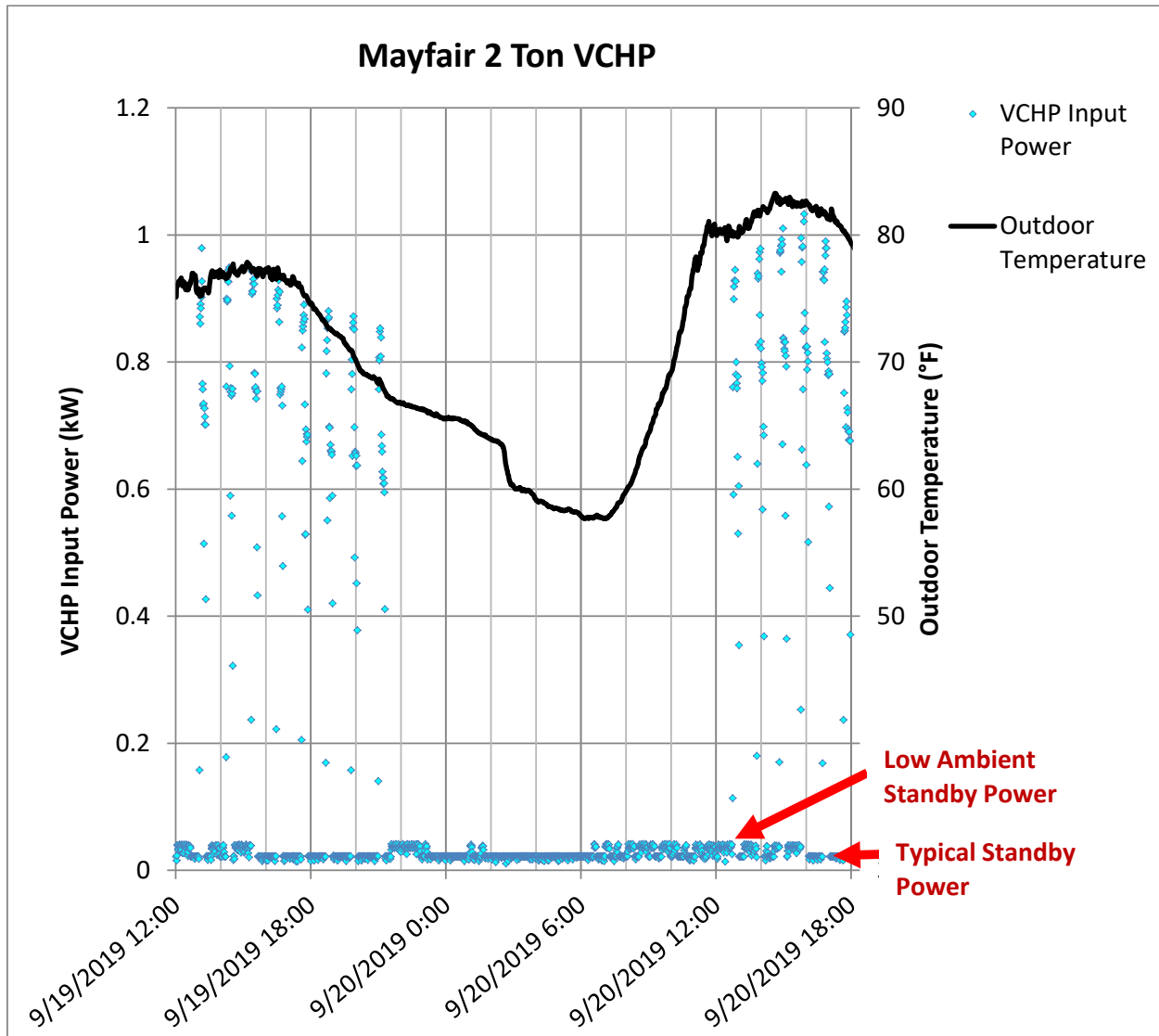


FIGURE 172. MAYFAIR 2 TON VCHP TEMPERATURE DEPENDENT STANDBY ENERGY

Typical standby power was assumed to be constant at all times and was not included in the crankcase heat energy analysis. Additional temperature dependent standby energy use above the constant typical standby power level was modeled by linear regression of the total daily temperature dependent standby energy against daily average outdoor temperature.

Seasonal temperature dependent standby energy use was calculated as:

$$kWh_{CCH} = \sum_{i=1}^{365} [Max(0, T_i \times F_T + C)]$$

Where:

T_i = Daily average outdoor temperature (°F) for day i , for each of 365 days in a year that are predicted to have cooling or heating loads greater than zero based on the modeled reference heating and cooling system energy use. The resulting crankcase heat energy use corresponds to days with cooling or heating energy use. It is not intended to reflect the full amount of crankcase heat that would occur over the entire year.

F_T = Linear regression daily energy use (kWh) slope against daily average outdoor temperature (°F)

C = Linear regression constant

TABLE 84. MAYFAIR VCHP TEMPERATURE DEPENDENT STANDBY ENERGY REGRESSIONS

SYSTEM	SEASON	F_T	C	R^2
1.5 Ton VCHP	Cooling	-.0136	1.106	.52
	Heating	.0037	-.1066	.21
2 Ton VCHP	Cooling	.0031	0.288	.55
	Heating	.0046	-.1882	.50

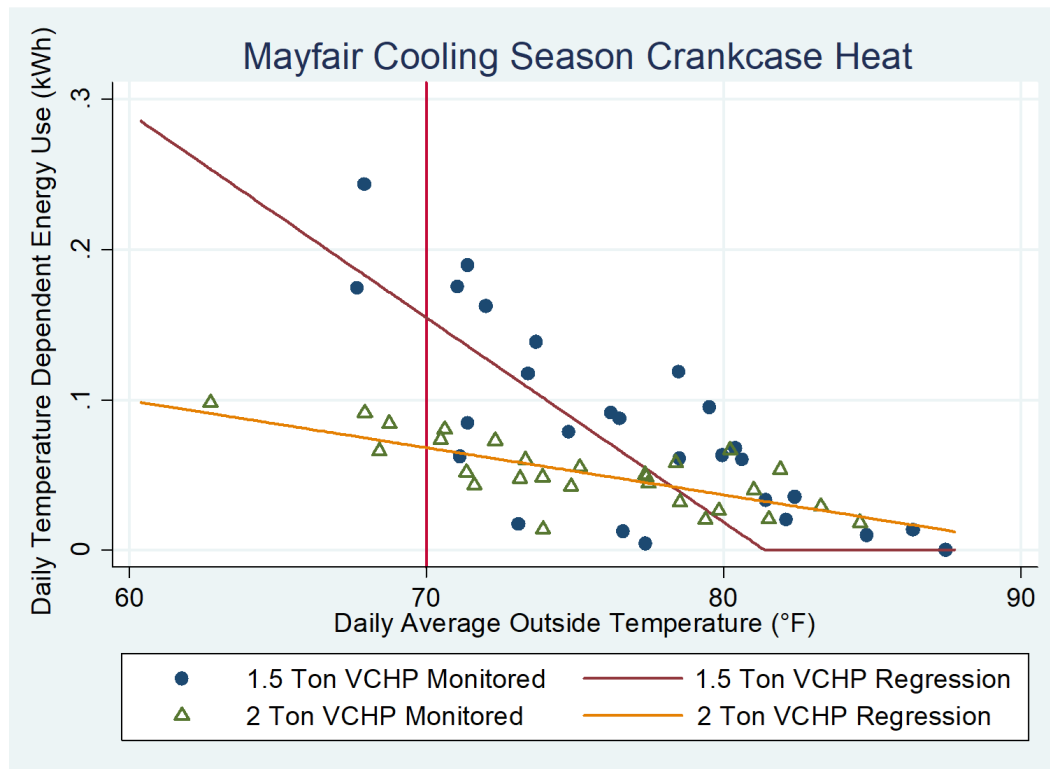


FIGURE 173. MAYFAIR TEMPERATURE DEPENDENT STANDBY ENERGY REGRESSIONS, COOLING SEASON

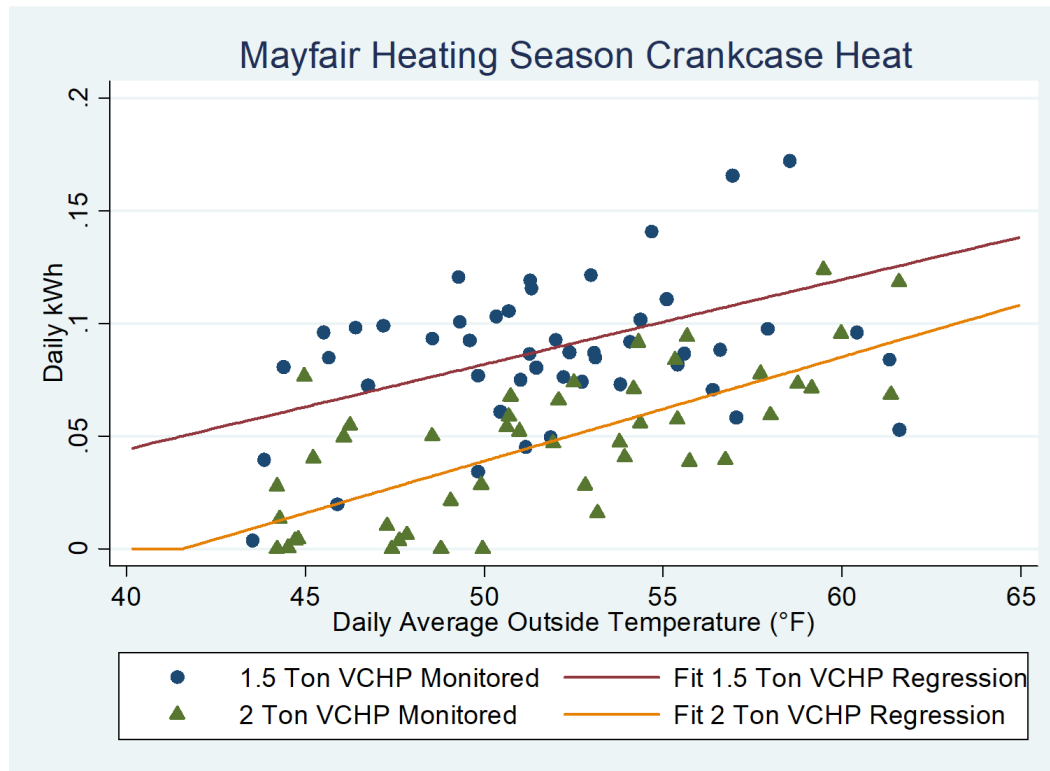


FIGURE 174. MAYFAIR TEMPERATURE DEPENDENT STANDBY ENERGY REGRESSIONS, HEATING SEASON