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Residential Crawl Space Conditioning and Sealing Retrofits

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Disclaimer

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EXECUTIVE SUMMARY

A field assessment at four existing residential sites was conducted over two years to study the effects and implications of conditioned crawl space retrofits. The findings can help determine which programs and stakeholders would need to be involved in future efforts, market transformation, or support roles. Energy usage, indoor air quality, market size, and market barriers were explored.

The measure under study is the sealing and conditioning of existing baseline, vented crawl spaces at single family residences. Sealed, conditioned crawl spaces have a vapor barrier on the earthen floor, insulation on the crawl space walls, and a pathway for conditioned air to circulate. The measure can improve building envelope air tightness, reduce duct leakage loads, reduce humidity levels, and improve overall air quality. It may also improve demand response effectiveness by increasing available cool air and thermal mass during an event. Past studies have found that the measure can achieve HVAC energy savings of 15-32% in new construction and eliminate excessive crawl space humidity.

The data and analysis showed a variety of results. The highest savings were observed in the in the hottest climate zone and with ducting in the crawl space. At two sites that were well controlled and had typical HVAC energy use patterns, electrical energy savings of 21-28% were observed while gas usage showed mixed results. Electrical savings were well-distributed over the daytime in the summer and demand response tests showed reductions similar to existing programs. Another site with window units saw similar savings of 19% but had low absolute energy usage due to atypical occupant preferences. The fourth site had inconclusive results that were either energy neutral or an increase uncorrelated to weather. This site had a baseline with a vapor barrier and also had unusual HVAC preferences.

Indoor air quality and humidity levels were improved in all cases. High humidity levels in the crawl spaces that can lead to mold and rot were virtually eliminated. The average measure cost was $8.7 per square foot but could likely be reduced with standardization and increased market adoption. The existing market size is approximately 1,387,700 and 441,600 homes in California and SCE territory, respectively. Of these that have central air, the estimated potential savings is on the order of 400 and 1,100 GWh/year for SCE and California, respectively, if the Fullerton and Desert Hot Springs sites are considered typical.

Recommendations for further measure support are a comprehensive modeling and sensitivity analysis like those done for codes and standards initiatives. This will allow for additional study of the measure under control of influential variables and building types. However, common building modeling software cannot model conditioned crawl spaces and a custom solution or software modification might be needed. Program support could include packaged residential rebates or incentives, energy accounting in the compliance process, and outreach and training for contractors to help foster market adoption and availability. Any program should target older homes with central air and ducting in the crawl space for best cost-effectiveness and most appropriate early adopters.

TABLE-ES 1. SUMMARY OF ENERGY SAVINGS AND DEMAND REDUCTION

HOST SITE	AVERAGE DR REDUCTION (KW)	ELECTRICITY SAVINGS (KWH/YR)	GAS SAVINGS (THERM/YR)
Desert Hot Springs	1.14	2,132 (28%)	40 (42%)
Fullerton	0.95	625 (21%)	-20 (-12%)
Pomona	n/a	91 (19%)	n/a

ABBREVIATIONS AND ACRONYMS

ACH50	Air changes per hour at 50 Pascals
CA	California
CBECC-Res	California Building Energy Code Compliance – Residential (software)
CCS	Conditioned crawl space
CDD	Cooling degree day
cfm	Cubic feet per minute
CO	Carbon monoxide
CZ	Climate Zone
DR	Demand response
HDD	Heating degree day
HVAC	Heating, ventilation, and air conditioning
IAQ	Indoor air quality
IAT	Indoor air temperature
kWh	Kilowatt-hour
OARH	Outside air relative humidity
OAT	Outside air temperature
pCi/L	Picocurie per liter
PCT	Programmable communicating thermostat
ppm	Parts per million
SCE	Southern California Edison
SFR	Single family residence

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INTRODUCTION

Residential heating, ventilation, and air conditioning energy usage is affected by many variables. These include occupant comfort preferences and behavior, primary equipment specifications and maintenance, weather, and building characteristics. Building characteristics include parameters such as thermal resistance, air leakage, duct design, and other construction features. In general, as houses age and the building characteristics degrade energy consumption tends to increase. For instance, building leakage typically gets worse over time without corrective action and HVAC energy increases, compounded by aging equipment. Thus, retrofits on older homes can often save more energy than in newer homes – although this sometimes comes with added measure complexity and cost of implementation.

In buildings that have them, the design and integrity of crawl spaces are critical and can impact the energy needed for heating and air conditioning. A crawl space is the space underneath a house that is typically below or on grade underneath the floor - essentially a shallow, unfinished basement which can serve as a space for piping, ducting, conduit, floor supports, underfloor insulation, and other building components.

Crawls spaces can be categorized as conditioned or unconditioned and vented or unvented. Unconditioned crawl spaces have no air transfer between the HVAC system or living space and typically have vents to the outside which are meant to allow for passive ventilation. Unconditioned crawl spaces sometimes have insulation under the living space floor, between the crawl space and living space. Unconditioned crawl spaces can have vapor barriers placed on the earthen floor to reduce thermal transfer to the soil, moisture transfer from the soil, and reduction of radon gas influx. However, most unconditioned crawl spaces do not have vapor barriers installed.

FIGURE 1 – UNCONDITIONED, VENTED CRAWL SPACE EXAMPLE

Conditioned crawl spaces have no venting to the outside and instead typically have insulated exterior walls and passive or forced air circulation with the HVAC system or living space. Conditioned crawl spaces typically have vapor barriers installed, often required by code.

High humidity conditions and condensation can appear in crawl spaces especially when hot humid temperatures during the day swing dramatically to cooler conditions at night. Moisture also transfers from bare soil floors into the crawl space. Excessive moisture in crawl spaces can cause issues such as dry rot, mold, termites, swelling, buckling, and poor indoor air quality (IAQ). It is typically recommended that relative humidity (RH) levels be kept below 70% to avoid condensation and moisture buildup that can cause these problems (EPA, 1991).

Traditional thinking was that venting of crawl spaces was an effective and affordable method of managing moisture. Early building codes required vented crawl spaces under the reasoning that natural ventilation driven by wind effects would help reduce humidity and remove standing or condensed water in crawl spaces. However, it has been concluded that there is no compelling evidence that vented, unconditioned crawl spaces are effective at managing moisture (ASHRAE, 1994). In fact, ground cover vapor barriers are often more effective at moisture management and can eliminate the need for venting in most locations (Rose & Ten Wolde, 1994). Additionally, vented crawl spaces are not necessarily lower cost since they often require a larger area of insulation (floor area versus wall area) especially in new construction when crawl space insulation is required or prudent (ASHRAE, 2017).

Additionally, there are energy implications to constructing vented, unconditioned crawl spaces. For instance, leaky ductwork located in vented crawl spaces can draw in humid, unconditioned air and increase cooling energy costs by 20-30% (Yost, 2003). A review of a large dataset of United States residential buildings found that building air tightness and envelope leakage was worst for homes with vented crawl spaces, especially older homes and with ductwork located in the crawl space (Chan, Joh, & Sherman, 2012).

To summarize, issues that can arise from vented, unconditioned crawl spaces include:

- Increased living space air leakage, exfiltration, and infiltration through floor
- Increased loads from leaky ducts in crawl spaces
- High moisture, dry rot, and mold potential in crawl space driven by moisture in earth and condensation
- Stack effect pulling cold air from crawl space into living space during winter
- Vermin and insect ingresses
- Compromised IAQ

Based on this evolving understanding of crawl space construction and moisture control, residential building codes have changed over the years to allow for sealed, unvented designs. The 2009 and 2012 International Residential Code was changed to allow for unvented crawl spaces and other building codes followed (US DOE). The 2016 California Residential Code (Title 24, Part 2.5, Section R408) stipulates that crawl spaces can be vented or unvented. If a crawl space is unvented, exposed earthen floors must have a continuous vapor barrier and must be either mechanically ventilated or have a supply of conditioned air with a return to the living area at a rate of 1 ft^3/min per 50 ft^2 of floor area (California Building Standards Commission, 2016).

Since these code changes are relatively recent, there is a large existing building stock with unconditioned, vented crawl spaces. For the purposes of this study, the baseline conditions are existing vented, unconditioned crawl spaces. Since this is a field case study of several existing homes, the baseline conditions are those found at the homes before any intervention as detailed in the Technical Approach section. These baseline conditions are similar to the large existing building stock with vented crawl spaces.

Crawl spaces are common in California. As shown in Figure 2, about 23% of California single family residence (SFR) homes built since 1971 have crawl spaces (US Census Bureau, 2017). However, recent years have shown a decreasing trend. Similarly, two studies have reported that approximately 20-21% of existing United States homes have crawl spaces (W.R. Chan, 2012) (Malkin-Weber, Coulter, Dixon, Dastur, & Davis, 2008). Of homes with crawl spaces, approximately 25% are sealed (Chan, Joh, & Sherman, 2012).

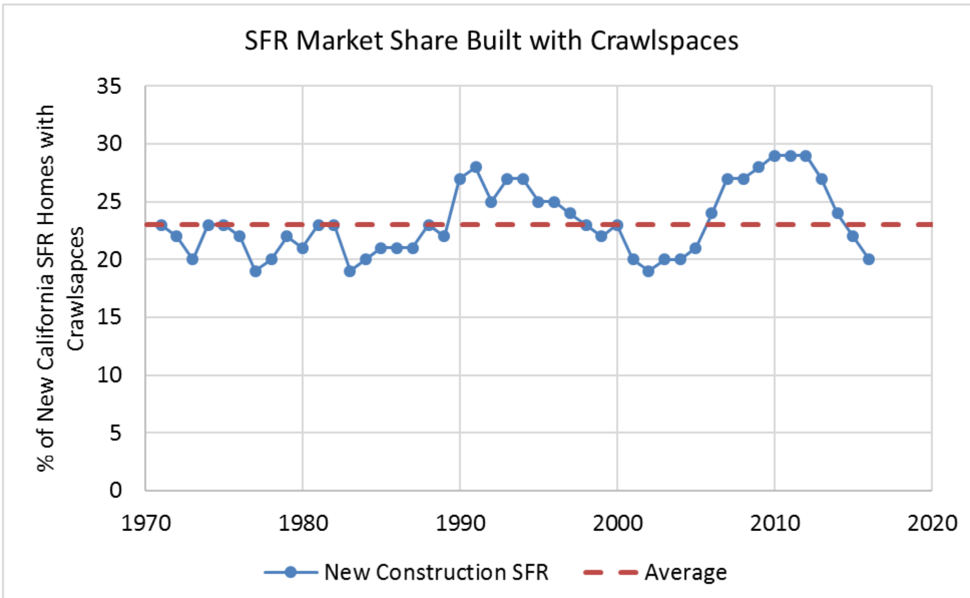

FIGURE 2 - CALIFORNIA SFR MARKET SHARE BUILT WITH CRAWL SPACES (US CENSUS BUREAU, 2017)

Based on a variety of market survey data sources, the potential existing market size can be estimated. This can be used to characterize the total energy efficiency resources available and target audience size for a retrofit, training, or code measure program.

According to the 2015 US Census, there are approximately 13,845,790 housing units in California, 58% of which are detached SFR buildings (US Census Bureau). Across the counties in SCE territory, about 56% of the homes are detached SFR buildings. Additionally, SCE's customer base accounts for about 33% of all California electric customers (California Energy Commission, 2014). Thus, since 23% of California SFR homes have crawl spaces and 75% of those are vented, the market size for this measure is approximately 441,600 buildings in SCE territory and 1,387,700 buildings in California. Across the United States, there are about 26 million existing homes with vented crawl spaces (Malkin-Weber, Coulter, Dixon, Dastur, & Davis, 2008).

TABLE 2 – ESTIMATED EXISTING MARKET SIZE[1] (DETACHED SFR BUILDINGS WITH CRAWL SPACES) AND ENERGY USE INTENSITY

REGION	MARKET SIZE (HOUSING UNITS)	AVERAGE ELECTRIC EUI (kWh/ft^2-YR)	AVERAGE GAS EUI ($therms/ft^2$-YR)
California	1,387,700	4.04	0.22
SCE Territory	441,600	4.00	0.22

[1] As of available 2015 data.

As stated above, homes with vented crawl spaces tend to have the highest leakage rates, especially if ductwork is located in the crawl space (Chan, Joh, & Sherman, 2012). Thus, single family homes with ductwork in vented crawl spaces would be the optimal target building type for this measure. Existing data was insufficient to determine how many homes ductwork in their crawl space, but roughly 66% of SFR buildings with crawl spaces will have central air in SCE territory and 56% statewide.

Since crawl space design has significant implications on building air tightness, it is also important to understand what the typical SFR leakage rate is. Average leakage rates for California homes has been reported to be approximately 14.6 and 5.5 air changes per hour at 50 Pascals (ACH50) for existing and new construction residences (after 2000), respectively (Sherman & Dickerhoff, 1998) (Sherman & Chan, 2013). Although California building code and compliance has measures and energy accounting for envelope tightness, there is no required maximum air leakage rate. The 2015 International Energy Conservation Code R402.4 specifies that new single-family residential buildings in California climate zones (CZ) should have leakage rates at or below 3 ACH50 (International Code Council), meaning that average existing California homes are about five times leakier than this code guideline. Some of this excessive air leakage travels through crawl space pathways.

EMERGING TECHNOLOGY BACKGROUND

As discussed above, there are several reasons why vented, unconditioned crawl space construction may not be ideal or necessary for moisture management. Recent code changes have made steps towards moving market adoption of unvented crawl spaces. However, adoption rates in new construction remain low and crawl space sealing retrofits of existing homes are negligible (Lstiburek, 2004).

This study was designed to gather data and draw conclusions on unvented, conditioned crawl spaces to provide information useful for market transformation. It evaluates the potential impacts of the measure in retrofit scenarios using field study at several California homes. Although sealing and conditioning crawl spaces can apply to either new construction or existing homes, this case study focused entirely on existing homes to evaluate the potential of the existing building stock. While costs and experimental controls are perhaps better in new construction, energy savings potential may be greater in less efficient, older existing homes. One study reported that bringing existing residences into compliance with 2013 Title 24 standards and improving air tightness could save 25,000 GWh per year in California (Sherman, Singer, Walker, & Wray, 2013).

Several studies over the last 20 years have quantified the moisture management and energy benefits of unvented, conditioned crawl spaces. One early study in a heating-intensive climate zone measured energy savings of 32% in a recently constructed building (Hill, 1998) after sealing and insulating the crawl space vents. The building had ductwork in the crawl space and the baseline included a vapor barrier and crawl space wall insulation, but once sealed, the crawl space did not have any air flow unlike today's recommendations. The author noted that savings would likely be higher in "more typical homes" because it was a particularly efficient baseline.

A side-by-side study of 12 new construction homes in North Carolina measured 15-18% HVAC energy savings for homes with crawl space sealing and forced-air conditioning as compared to similar baseline homes that also had vapor barriers and floor insulation (Dastur & Davis, 2005). The study also found that moisture levels were kept low enough to discourage problems such as shrinking, swelling, rot, and mold.

Several other studies have shown mixed results. A 2009 study found mixed savings around 15% at new construction test sites in Louisiana but neutral energy effects in Flagstaff (Dastur, Mauceri, & Hannas, 2009). However, the study did confirm that sealing would keep humidity within safe bounds regardless of climate zone or season. A study published in 2007 found little energy benefits to conditioning and sealing crawl spaces in a new construction test home in the Pacific Northwest (Building Industry Research Alliance, 2007). However, the study was also concerned with other measures, used an insulated floor baseline, and appears to have not included circulation of air through the crawl space. Finally, a side-by-side study of two high-efficiency, new construction homes in a mixed, humid climate found that there appeared to be an energy penalty associated with the measure the heating season but an energy benefit in the summer cooling months (Biswas, Christian, & Gehl, 2011). However, the results suggested that conditioned, sealed crawl spaces had little overall energy benefit compared to a vented crawl space with underfloor insulation.

Primary differences between past, referenced studies and this one is that the referenced studies focused on new construction and had different measure conditions. For instance, the baselines often had underfloor insulation. As such, it is difficult to compare these studies to each other or to this one. Instead, they together form a more comprehensive understanding of conditioned crawl spaces under different conditions.

The retrofit measure under study comprises a vapor barrier that covers all crawl space ground and wall area. Furthermore, since existing crawl space wall and vent geometries can be irregular and interface with the outside, rigid spray foam sealing and insulation can also be applied on the crawl space interior walls over the vapor barrier. For any external crawl space entries, an insulated cover with a tight-fitting gasket can be applied at the entry to complete the sealing integrity while still allowing exterior access. Additionally, the crawl space can be conditioned and ventilated by supplying an airflow path using transfer registers, ductwork, or fans. For instance, ductwork in the crawl space can be modified to have returns or supplies in the crawl space and vents in the floor can allow air flow between the crawl space and living space.

FIGURE 3 – VAPOR BARRIER AND INSULATION AFTER MEASURE IMPLEMENTATION

Potential benefits of these measures include:

- Reduced envelope leakage, infiltration, and exfiltration
- More thermal mass available to smooth out interior temperature response to outside temperatures and enhance demand response (DR) potential.
- Improved insulation over existing baseline conditions
- Reduced risk of dry rot, wood deformation, pests such as termites, standing water, and mold
- Reduced duct leakage with unconditioned air if ducts located in crawl space

In total, the emerging technology in this study is a suite of measures that includes:

- Vent and entry sealing with a vapor barrier on the walls and ground
- Spray foam insulation of the crawl space exterior walls
- Forced conditioning via return ducts (or a fan in ductless homes) and transfer registers to the living space
- Programmable communicating thermostat (PCT) to enable DR control via remote signals

The construction measures (excluding the PCT) had varying costs across the four sites due to their unique needs and HVAC equipment. Note that the Murrieta site's baseline included a crawl space that had a vapor and moisture barrier on the soil floor (although it was not sealed or conditioned). As such, the Murrieta project costs were lower than the others. Table 3 and Table 4 list the total and per square foot measure costs.

TABLE 3 – CRAWL SPACE MEASURE CONSTRUCTION COSTS

HOST SITE	INSULATION AND SEALING ($)	HVAC COST ($)	TOTAL MEASURE COST ($)
Desert Hot Springs	$6,917	$4,000	$10,917
Fullerton	$8,828	$2,300	$11,128
Murrieta	$4,320	$2,200	$6,520
Pomona	$8,071	$2,500	$10,571

TABLE 4 – CRAWL SPACE MEASURE COSTS PER SQUARE FOOT

HOST SITE	INSULATION AND SEALING ($/FT^2)	HVAC COST ($/FT^2)	TOTAL MEASURE COST ($/FT^2)
Desert Hot Springs	$7.69	$4.44	$12.13
Fullerton	$7.24	$1.89	$9.12
Murrieta	$2.88	$1.47	$4.35
Pomona	$6.96	$2.16	$9.11

ASSESSMENT OBJECTIVES

Since conditioned crawl space retrofits are not well understood, research is needed to decide whether to allocate resources towards further study and to decide which statewide and utility programs are most aligned with the measure's potential. For instance, the measure may have overlap with energy efficiency programs, DR programs, codes and standards, building modeling software development, and others. The findings can help determine which of these programs and their stakeholders would need to be involved in future efforts, market transformation, or support roles.

To that end, this study has several objectives:

1. Measure energy usage and estimate savings of residential unvented, conditioned retrofit crawl spaces.
2. Perform DR tests to establish whether crawl space measures improve residential HVAC DR effectiveness.
3. Explore residential building and compliance whole building modeling and investigate the compatibility of existing software with conditioned crawl spaces.
4. Measure indoor air quality metrics to ensure crawl space sealing is not detrimental to health.
5. Provide findings and recommendations for emerging technology, energy efficiency program, demand response program, and code readiness purposes.
6. Provide data and analytical results in a field assessment report for public dissemination to increase understanding of the measures in a retrofit case.

To achieve these objectives, a field assessment at four existing residential sites was conducted over two years. The first year was for baseline monitoring while the second year was for measure monitoring. The Technical Approach sections go into more detail on data collected, project timelines, host site conditions, and other measurement and analysis plan specifics.

TECHNICAL APPROACH

Since the research concerned retrofit applications of the measure, it was studied in a field assessment at four existing SFR buildings across SCE territory. Table 5 outlines some primary characteristics of the sites. The sites had higher energy use intensities than the average California home and average building air leakage except for the Pomona site. The host sites were selected based on appropriateness for the retrofit measures, representativeness of typical existing residential building stock, and willingness to participate in an extended testing engagement. Since the test was invasive and extensive, participant willingness was a primary constraint in site recruitment. Due to the small sample size, the field assessment is meant to be a case study more than an analysis representative of market-wide potential or impacts, such as a building modeling assessment across prototype building conditions or a large population.

TABLE 5 - HOST SITE OVERVIEW

HOST SITE	CA CZ	YEAR BUILT	BASELINE LEAKAGE (ACH50)[2]	LIVING SPACE AREA (FT^2)	BASELINE ENERGY INTENSITY (KWH/FT^2-YR)[3]	BASELINE ENERGY INTENSITY ($THERM/FT^2$-YR)[4]
Desert Hot Springs	15	1946	15.3	900	13.48	0.30
Fullerton	8	1957	13.2	1,220	5.07	0.22
Murrieta	10	1980	13.7	1,500 (1st floor) 940 (2nd floor)	4.33	n/a
Pomona	9	1920	37.6	1,160	7.36	n/a

Table 6 outlines the baseline conditions and measure specifics that were unique to each test site.

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[2] Average envelope air leakage of California existing homes is about 14.6 ACH50 (Sherman & Dickerhoff, Air-Tightness of U.S. Dwellings, 1998).

[3] Average energy intensities of California single-family homes are about 4.0 kWh/ft^2 and 0.22 $therms/ft^2$ for homes with gas service (KEMA, 2010).

[4] The Murrieta and Pomona sites do not have any natural gas heating.

TABLE 6 – BASELINE AND MEASURE SPECIFICS

HOST SITE	HVAC SYSTEM	SYSTEM SIZE (COOLING BTU/HR)	BASELINE CRAWL SPACE	MEASURE CRAWL SPACE AIR FLOW
Desert Hot Springs	Packaged unit with gas heat, ducted through crawl space with floor registers	36,000	Soil floor, vented, duct work, one exterior entry	10"x10" return duct in crawl space to draw when HVAC fan running. Floor registers at house perimeter foster airflow between living space and crawl space
Fullerton	Split system with gas heat, ducted through attic with ceiling registers	36,000	Soil floor, one exterior entry	8"x8" hole cut into closet air handler return plenum, allowing air to be drawn from crawl space when HVAC fan in operation. Floor registers at the four corners of the house foster airflow between living space and crawl space
Murrieta	(Lower Level) Package heat pump, ducted through crawl space with floor registers (Upper Level) Whole house fan and two window units	30,000 (heat pump) 5,000 (each window unit)	Vapor barrier, duct work, vented, interior entry	10"x10" return duct in crawl space to draw when HVAC fan running. Floor registers at house perimeter foster airflow between living space and crawl space
Pomona	Two window units in bedrooms, no heat, no ductwork	9,000 and 7,000	Soil floor, vented, three exterior entries	Floor register with flexible duct and fan installed in crawl space to force air into living space. Three floor registers installed in three corners of house to foster airflow between living space and crawl space

Although the timelines and monitored data points varied slightly for each site due to their unique conditions and constraints, the overall, general project timeline is shown in Figure 4. The baseline was considered existing conditions and was measured for roughly three seasons, from May to February. The second phase which started after the installation of a PCT, crawl space sealing, and HVAC alterations was measured for roughly one year following the baseline.

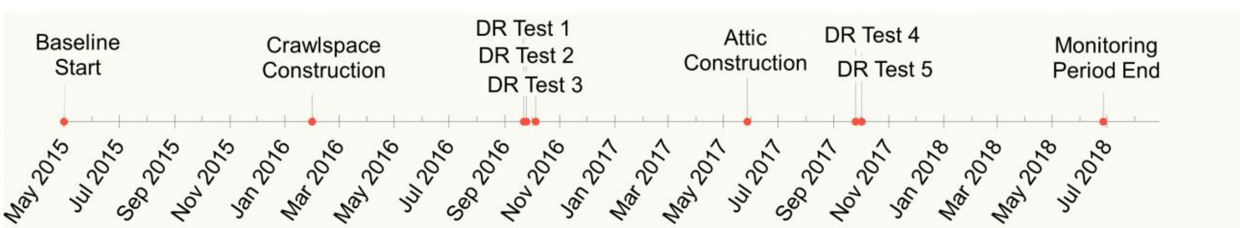

FIGURE 4 – PROJECT TIMELINE

Instrumentation and data collection points were selected to gain a complete perspective of the building response the measure in line with International Performance Monitoring and Verification Protocol guidelines. Measurement points were selected to follow IPMVP Options B (Retrofit Isolation All Parameter Measurement) and C (Whole Facility). Under Option B measurements are taken at all building parameters and energy consumption points that are necessary to establish normalized energy savings at the systems affected by the measures. Gas usage and savings were determined using Option C by utilizing gas billing data instead of independent sub-system measurement. Additionally, several other data points were collected to confirm that the measures did not negatively affect IAQ and building health metrics.

The measurement points and instrumentation are listed in Table 7. Additional details on instrumentation and data points for each site are listed in the next site description sections.

Table 7 – Data Collection Points and Instrumentation Overview

Measurement	Instruments	Logging Interval
Power monitoring (fans, condensers, compressors, package units, window units)	CTs with amperage data loggers, spot measurements of power factor and voltage	1 minute
Natural gas usage	Southern California Gas utility metering	Billing period
Temperature and relative humidity – indoor, outdoor, attic, and crawl space	Onset HOBO sensors and data loggers	15 minutes
HDD and CDD	Local airport weather station	1 hour
Soil temperature	Onset HOBO sensors and data loggers	15 minutes
Carbon monoxide – indoor, outdoor, attic, and crawl space	Dwyer CO data logger	5 minutes
Indoor radon	Family Safety Products Safety Siren	Short and long-term averages

Although data was logged at intervals of 1, 5, and 15 minutes, the data was eventually consolidated to hourly and daily intervals. Analysis began at small intervals but the response times of the building and the regression analysis required a longer interval to establish usable regression equations. At all sites, data was stored in onsite loggers and manually retrieved periodically (roughly every three months). While this did result in some data gaps due to monitoring malfunctions between data collection site visits, instrumentation was checked regularly for quality assurance.

Since the residential host sites were private and had to be treated sensitively, not all variables could be controlled. For instance, space temperature setpoints, occupied hours, HVAC scheduling, building maintenance, personal preferences, and other such variables were out of the experimental control. For tighter control of all relevant experimental variables and true measure isolation, unoccupied building or lab testing under controlled conditions would be required.

Data was used to establish energy usage relationships to independent weather variables. By establishing normalized energy usage relative to weather, controlled energy usage before and after measure implementation can be compared. Non-weather variables were explored for normalization (such as weekday, season, and time of day), but only weather and indoor air temperature (IAT) were found to be significant variables in the analysis.

To calculate normalized energy savings, linear regression equations for each building's electrical and natural gas energy were calculated. In general, these regression relationships took the following form.

$$E = a + b * OAT + \mathrm{c} * OAT^2 + d * IAT + \mathrm{e} * (OAT - IAT)$$

where E is daily electrical or natural gas energy, OAT is the outdoor air temperature, and IAT is the indoor air temperature. Note that not all variables were needed for each site and regressions of many forms with differing independent variables were tested for viability, ultimately selected based on statistical significance and accuracy. IAT was necessary in some cases where the indoor temperatures differed significantly between monitoring periods or when an accurate regression to only *OAT* could not be established.

Normalized, annual energy usage was calculated with the regression equations using average weather conditions for the individual host site locations. Outside air temperatures were averaged across three years of local weather station data so that an annual, localized weather pattern could be used. This was used in addition to CA CZ weather data because host site local weather differs from CZ representative datasets and the measurement plan was designed as a case study. Results for both local weather station and CZ data are presented.

PACKAGED AC WITH GAS HEAT - DESERT HOT SPRINGS

The Desert Hot Springs site was a 900-square foot home with a 2-year old, 13 SEER, 3-ton packaged unit with an 80% AFUE gas furnace rated at 60 MBtu/hr. The two occupants were observed to have high annual occupied hours. The baseline unfinished crawl space had a dirt floor, an exterior entrance, no crawl space insulation, and insulated flexible ductwork. The HVAC system was controlled by a single setpoint thermostat. The attic had 13 inches of R11 blown insulation and the single pane windows were not tinted.

The measurement points in the home are shown in Table 8. Although each site differed somewhat, the same types of data were monitored at each site and for each phase (baseline and measure case).

TABLE 8 - DESERT HOT SPRINGS MEASUREMENTS

MEASUREMENT	UNIT	LOGGING INTERVAL	EQUIPMENT
Package Unit Current	Amps	1 minute	Onset HOBO data logger and current transducer
Packaged Unit Voltage and Power Factor	V and pf	Spot measurements	Extech Clamp Multimeter
Outside, Inside, Attic, and Crawl Space Air Temperature	°F	15 minutes	Onset HOBO data loggers and sensors
Outside, Inside, Attic, and Crawl Space Air Relative Humidity	%	15 minutes	Onset HOBO data loggers and sensors
Outside Air Temperature and Degree Days	°F and DD	Sub-hourly	Local weather station data service
Outside Air Relative Humidity	%	Sub-hourly	Local weather station data service
Natural Gas Usage (whole building)	therm	Billing period	SoCalGas utility-grade meter
Crawl Space 6-inch Subsurface Soil Temperature	°F	1 minute	Onset HOBO data logger and sensor
Crawl Space 18-inch Subsurface Soil Temperature	°F	1 minute	Onset HOBO data logger and sensor
Outside, Inside, Attic, and Crawl Space Carbon Monoxide	ppm	5 minutes	Lascar CO EL-USB-CO300 data logger
Inside Radon Levels	PCi/L	Running average	Safety Siren Series 3 Radon Meter

SPLIT SYSTEM WITH GAS HEAT - FULLERTON

The Fullerton site was a 1,220-square foot home with a new 13 SEER 3-ton split system with an 80% AFUE gas furnace and three occupants. The baseline unfinished crawl space had a dirt floor, an exterior entrance, and no insulation. The HVAC system was controlled by a single setpoint manual thermostat and the attic had 10 inches of blown insulation and ductwork from the centrally-located air handler. The closet air handler had a pedestal return drawing from the hallway before a hole into the crawl space was added during the measure construction.

The measurement points in the home are shown in Table 9.

TABLE 9 - FULLERTON MEASUREMENTS

MEASUREMENT	UNIT	LOGGING INTERVAL	EQUIPMENT
Outdoor Condenser/Compressor Unit Current	Amps	1 minute	Onset HOBO data logger and current transducer
Outside Unit Voltage and Power Factor	V and pf	Spot measurements	Extech Clamp Multimeter
Inside Evaporator Air Handler Unit Power	kW	1 minute	Onset HOBO UX120-018 Plug Load Logger
Outside, Inside, Attic, and Crawl Space Air Temperature	°F	15 minutes	Onset HOBO data loggers and sensors
Outside, Inside, Attic, and Crawl Space Air Relative Humidity	%	15 minutes	Onset HOBO data loggers and sensors
Outside Air Temperature and Degree Days	°F and DD	Sub-hourly	Local weather station data service
Outside Air Relative Humidity	%	Sub-hourly	Local weather station data service
Natural Gas Usage (whole building)	therm	Billing period	SoCalGas utility-grade meter
Crawl Space 6-inch Subsurface Soil Temperature	°F	1 minute	Onset HOBO data logger and sensor
Crawl Space 18-inch Subsurface Soil Temperature	°F	1 minute	Onset HOBO data logger and sensor
Outside, Inside, Attic, and Crawl Space Carbon Monoxide	ppm	5 minutes	Lascar CO EL-USB-CO300 data logger
Inside Radon Levels	PCi/L	Running average	Safety Siren Series 3 Radon Meter

SUPPLEMENTED PACKAGED HEAT PUMP - MURRIETA

The Murrieta site was a 2,440-square foot, 2-story home with a 10 SEER, 6.8 HSPF 2.5-ton packaged heat pump system conditioning the lower floor and two ½-ton window units for cooling on the upper floor. Additionally, the house has a whole house fan on a wall toggle switch in the second story attic. The baseline unfinished crawl space had a vapor and moisture barrier on the floor, an interior entrance, outside venting, insulated supply and return ducting, and no crawl space insulation. The heat pump was controlled by a single thermostat in the existing baseline while the window units were used occasionally in the summer in the upper floor. The attic had about 8 inches of bat insulation with moderate coverage.

The measurement points in the home are shown in Table 10.

TABLE 10 - MURRIETA MEASUREMENTS

MEASUREMENT	UNIT	LOGGING INTERVAL	EQUIPMENT
Packaged Unit Current	Amps	1 minute	Onset HOBO data logger and current transducer
Packaged Unit Voltage and Power Factor	V and pf	Spot measurements	Extech Clamp Multimeter
Window Unit Power	kW	1 minute	Onset HOBO UX18-120 plug load logger
Outside, Inside, Attic, and Crawl Space Air Temperature	°F	15 minutes	Onset HOBO data loggers and sensors
Outside, Inside, Attic, and Crawl Space Air Relative Humidity	%	15 minutes	Onset HOBO data loggers and sensors
Outside Air Temperature and Degree Days	°F and DD	Sub-hourly	Local weather station data service
Outside Air Relative Humidity	%	Sub-hourly	Local weather station data service
Crawl Space 6-inch Subsurface Soil Temperature	°F	1 minute	Onset HOBO data logger and sensor
Crawl Space 18-inch Subsurface Soil Temperature	°F	1 minute	Onset HOBO data logger and sensor
Outside, Inside, Attic, and Crawl Space Carbon Monoxide	ppm	5 minutes	Lascar CO EL-USB-CO300 data logger
Inside Radon Levels	PCi/L	Running average	Safety Siren Series 3 Radon Meter

WINDOW UNITS - POMONA

The Pomona site was a 1,160-square foot home with two 9.7 EER window units for cooling, each installed in bedrooms. The baseline unfinished crawl space had a dirt floor, three exterior entrances, outside venting, and no crawl space insulation. The attic had poorly distributed loose fill insulation with obvious bare, uninsulated gaps.

The measurement points in the home are shown in Table 11.

TABLE 11 - POMONA MEASUREMENTS

MEASUREMENT	UNIT	LOGGING INTERVAL	EQUIPMENT
Window Unit Power	kW	1 minute	Onset HOBO UX18-120 plug load logger
Transfer Fan Current	Amp	1 minute	Onset HOBO and CT
Transfer Fan Voltage	V	Spot	Extech Clamp Multimeter
Outside, Inside, Attic, and Crawl Space Air Temperature	°F	15 minutes	Onset HOBO data loggers and sensors
Outside, Inside, Attic, and Crawl Space Air Relative Humidity	%	15 minutes	Onset HOBO data loggers and sensors
Outside Air Temperature and Degree Days	°F and DD	Sub-hourly	Local weather station data service
Outside Air Relative Humidity	%	Sub-hourly	Local weather station data service
Crawl Space 6-inch Subsurface Soil Temperature	°F	1 minute	Onset HOBO data logger and sensor
Crawl Space 18-inch Subsurface Soil Temperature	°F	1 minute	Onset HOBO data logger and sensor
Outside, Inside, Attic, and Crawl Space Carbon Monoxide	ppm	5 minutes	Lascar CO EL-USB-CO300 data logger
Inside Radon Levels	PCi/L	Running average	Safety Siren Series 3 Radon Meter

RESULTS

The baseline and post-measure energy use was compared for each site to ascertain the energy savings potential of the measures. Additionally, some IAQ parameters were measured and DR tests were performed under the measure case (the baseline controls did not allow for DR testing). In all cases, comfort conditions improved in the living space. Inside air temperature and RH stayed closer to the typical comfort range over the observed range of outside air conditions. Additionally, radon and carbon monoxide levels were not adversely affected and tended to stay within safe bounds, in both the baseline and post-measure cases. Humidity in the crawl space improved in all cases and excessive levels that could lead to moisture problems were virtually eliminated.

Unless otherwise specified, energy figures refer to HVAC usage only.

Table 12 summarizes the energy savings achieved from the crawl space measure after normalization to local weather station data. Results are further detailed in each subsequent host site section. The Murrieta site results were inconclusive or showed that the measure had little effect on energy use as discussed in the following sections and Appendix B.

TABLE 12 - CRAWL SPACE MEASURE PHASE FINDINGS AND SAVINGS – NOMINAL AND % OF BASELINE

HOST SITE	ENVELOPE LEAKAGE REDUCTION @50 PA (CFM)	AVERAGE DEMAND RESPONSE REDUCTION[5] (KW)	ELECTRICITY SAVINGS (KWH/YR)	WHOLE BUILDING ELECTRIC EUI REDUCTION (KWH/FT^2-YR)	NATURAL GAS SAVINGS (THERM/YR)	WHOLE BUILDING GAS EUI REDUCTION (THERM/FT^2-YR)
Packaged AC with Gas Heat - Desert Hot Springs	280 (15%)	1.14	2,132 (28%)	2.37 (18%)	40 (42%)	.04 (15%)
Split System with Gas Heat – Fullerton	-605 (-28%)[6]	0.95	625 (21%)	0.51 (10%)	-20 (-12%)	-.02 (-7%)
Window Units – Pomona	73 (1%)	n/a[7]	91 (19%)	0.10 (1%)	n/a	n/a

[5] Average DR reduction for California SFR programs is about 1.09 kW (Southern California Edison, 2009).

[6] Since energy consumption went down, this may have been a faulty air leakage reduction measurement. Measurement after another measure post-crawl space study showed the same leakage as the baseline.

[7] DR tests at Pomona were not possible due to reliance on only window units with no DR capabilities.

HVAC energy usage and savings were also calculated for each site using California CZ weather data. Table 13 list the estimated savings for each building if located in each CZ and its respective weather patterns. Note that these extrapolations to the various zones are all based on one example for each type of building and should be considered as a set of case studies rather than a statistically significant dataset. The results are discussed in the Discussion and Conclusions section.

TABLE 13 – CRAWL SPACE MEASURE SAVINGS ACROSS CLIMATE ZONES[8]

	Baseline Electricity Usage (kWh/yr)				Electricity Savings (kWh/yr)				Baseline Natural Gas Usage (therm/yr)				Natural Gas Savings (therm/yr)			
	CZ8	CZ9	CZ10	CZ15	CZ8	CZ9	CZ10	CZ15	CZ8	CZ9	CZ10	CZ15	CZ8	CZ9	CZ10	CZ15
Packaged AC with Gas Heat - Desert Hot Springs Building Type	764	972	1,549	7,960	26	13	199	2,371	292	273	290	156	156	144	159	82
Split System with Gas Heat - Fullerton Building Type	1,532	1,811	2,285	6,464	33	166	326	2,267	397	383	434	224	-10	-8	2	-5
Window Units - Pomona Building Type	50	145	303	1,778	-47	-16	86	852	n/a				n/a			

[8] Negative values indicate increased energy consumption.

CARBON MONOXIDE, CRAWL SPACE HUMIDITY, & RADON

One concern with reducing outside air ventilation is carbon monoxide (CO) levels in the living space. Carbon monoxide is produced from fuel-burning appliances and equipment such as furnaces, water heaters, and stoves. Elevated levels of CO can be toxic and life-threatening. There are several recommended exposure limit standards by various agencies although there is no statewide code except a mandate that new single-family residences have approved CO alarms installed. ASHRAE 62.2 recommends a long-term exposure limit of 9 ppm for indoor residences. In recent years, the EPA has reported background, metropolitan area CO levels of under 5 ppm in the southwest region that includes California (Environmental Protection Agency, 2013).

Figure 5 shows the measured daily average CO levels inside and outside the Desert Hot Springs residence over the baseline and crawl space measure periods. It is obvious that inside CO levels do not increase to unsafe levels due to the measure. Note that the data logger had a rated accuracy of ±5 ppm, designated by the dashed line above the measured averages.

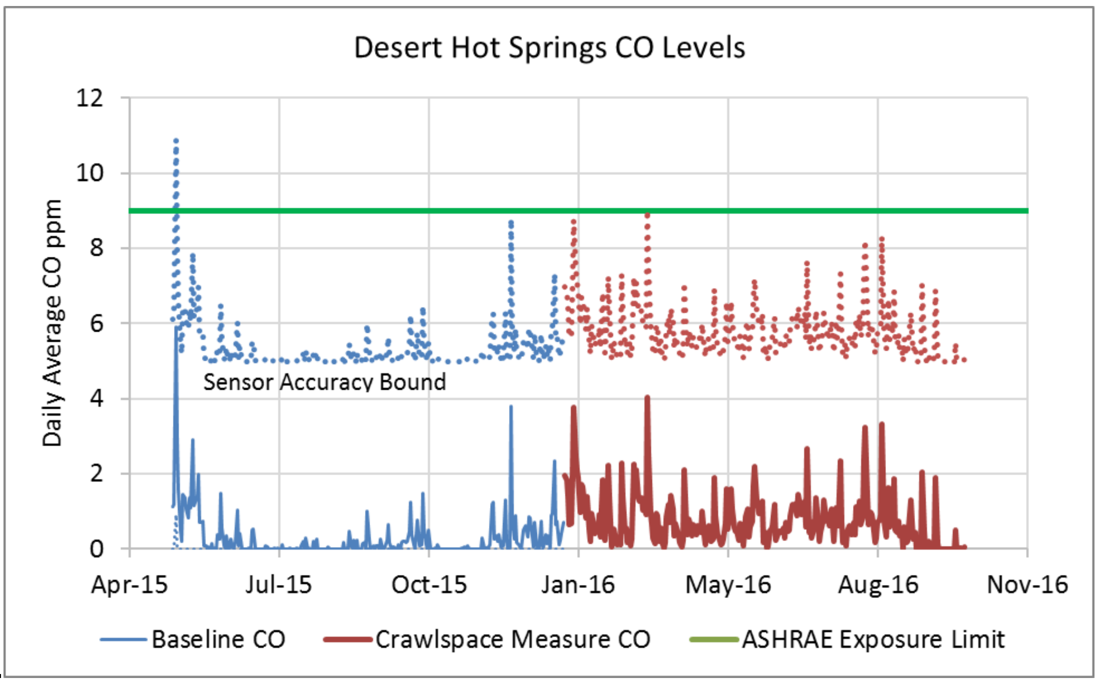

FIGURE 5 - DESERT HOT SPRINGS CARBON MONOXIDE MONITORING

Similarly, no significant increases or unsafe levels were apparent after the crawl spaces in the other homes were sealed and conditioned. Figure 6, Figure 7, and Figure 8 show the baseline and measure case indoor CO levels recorded for the other three sites. These figures support the conclusion that CO concentrations inside the living space were not negatively affected or increased to unsafe levels due to the measure.

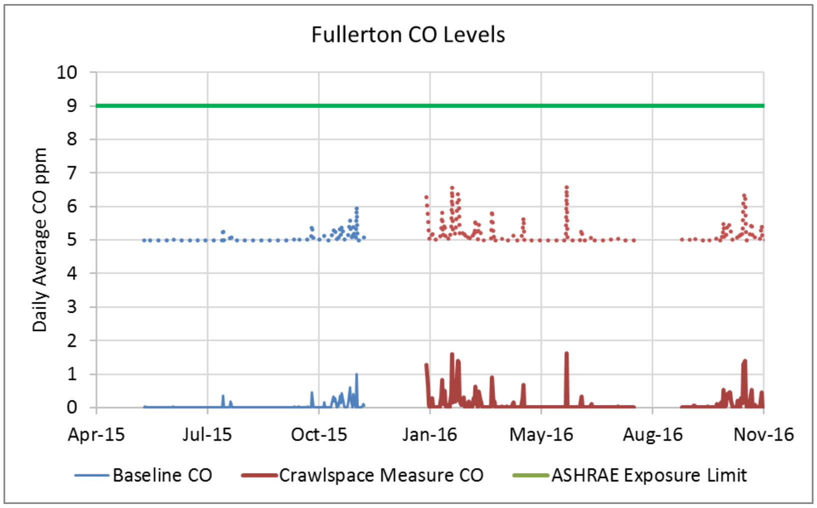

Figure 6 - Fullerton Carbon Monoxide Monitoring

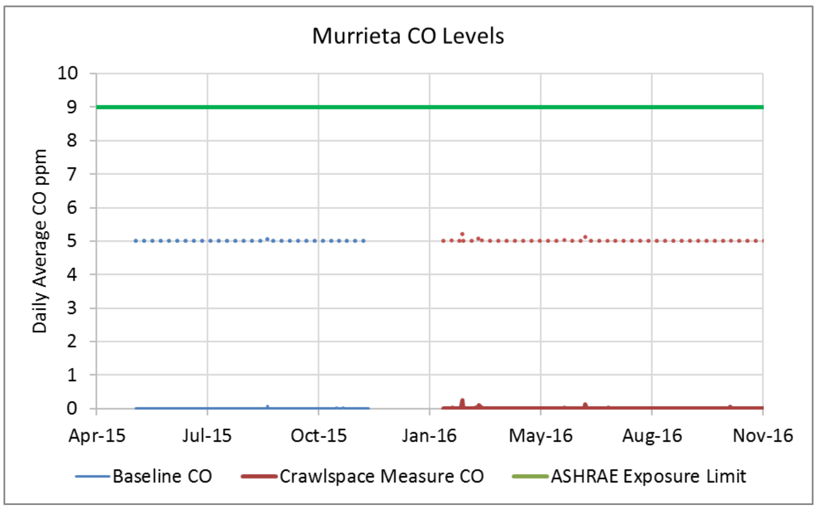

Figure 7 - Murrieta Carbon Monoxide Monitoring

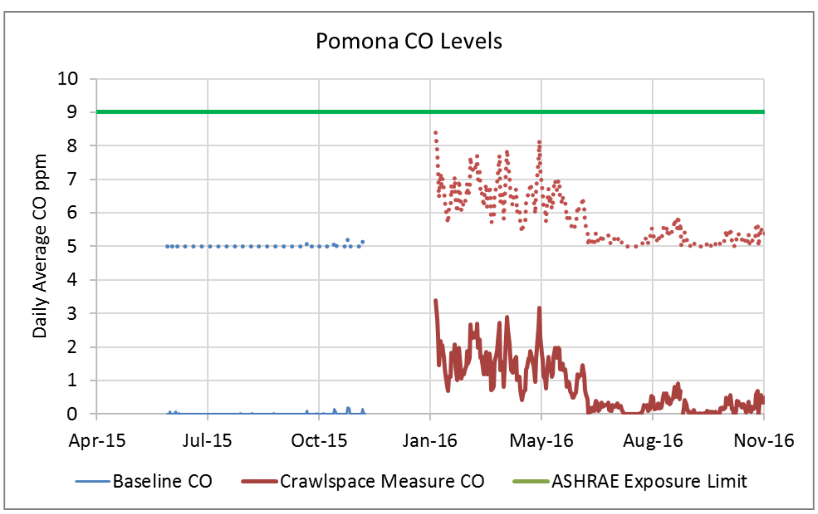

Figure 8 - Pomona Carbon Monoxide Monitoring

Another air quality and building integrity concern with crawl spaces is the buildup of moisture. This can occur due to a combination of poor ventilation and transfer of moisture from the soil and outside air into the building spaces, especially when there is a large temperature difference between day and night. It is typically recommended that RH levels be kept below 70% to avoid condensation and moisture buildup that can result in mold growth (EPA, 1991).

The reduction in slope from baseline to post measure case in Figure 9 shows that the crawl space air humidity had less dependence on outside air conditions, meaning that less air infiltration resulted in lower humidity, generally. This is shown by the lower overall average crawl space humidity in the post measure case. Although crawl space humidity increased at the lower end of the humidity range, the greater concern is at the higher range of RH. Sealing of the crawl spaces showed reduced humidity at the higher end of the range for all sites. In fact, the baseline monitoring observed many days with average humidity above the threshold of 70% while the post crawl space sealing period had only one day in Pomona above 70%. The Fullerton, Murrieta, and Pomona sites went from having 1-4% of the time spent above 70% crawl space relative humidity to 0%. Thus, the measure is an obvious benefit in terms of moisture reduction and mold prevention and will keep humidity below recommended limits.

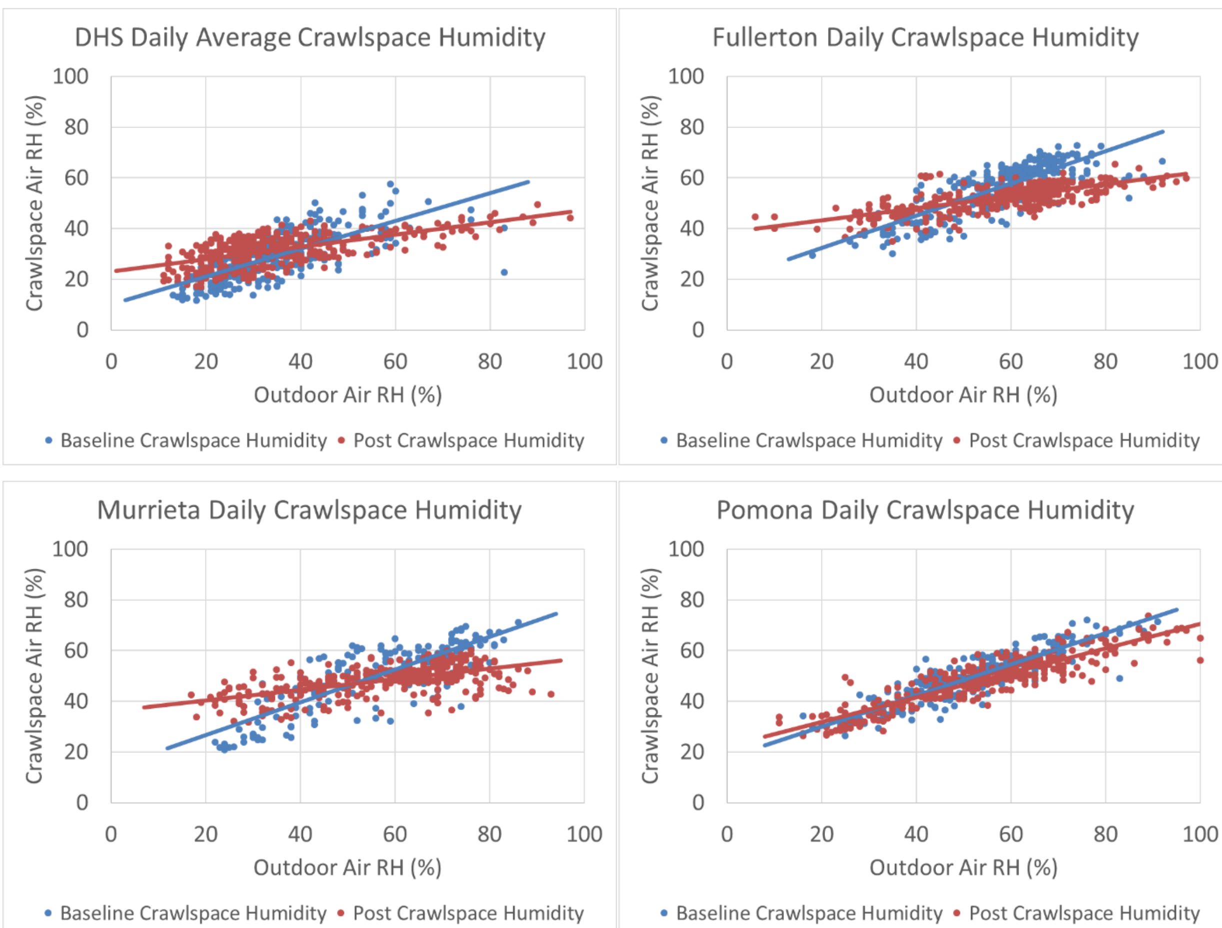

FIGURE 9 – CRAWL SPACE AIR HUMIDITY RELATIONSHIP TO OUTSIDE AIR HUMIDITY

Another indoor health metric that needs to be observed is radon levels in the home. Radon, measured in pCi/L, can enter the house due to release from the soil and rocks at the foundation. Mitigation of high levels of radon often involves forced ventilation of crawl spaces. Thus, it is conceivable that sealing of crawl spaces could potentially affect the levels of radon entering and accumulating in the home. However, vapor barriers can prevent radon from entering the house as well. Although there is no standard dictating safe levels of radon in the home, mitigation is typically recommended if levels are above 4 pCi/L (Environmental Protection Agency, 2012). Household alarms typically sound alerts when levels exceed that value.

Table 14 lists the recorded long-term average radon levels measured in the living spaces of each home. The data did not provide conclusive evidence on whether the sealing affected indoor radon levels positively or negatively. In any case, the measures did not increase any sites' radon readings above 4.0 and decreased the only site that saw levels above recommended limits.

TABLE 14 – LONG-TERM LIVING SPACE RADON READINGS

HOST SITE	BASELINE RADON LEVEL (PCI/L)	POST CRAWL SPACE MEASURE RADON LEVEL (PCI/L)
Desert Hot Springs	0.8	1.8
Fullerton	1.7	2.6
Murrieta	1.2	1.3
Pomona	5.5	4.6

PACKAGED AC WITH GAS HEAT - DESERT HOT SPRINGS

The Desert Hot Springs site is a 1946 single-story building with 900 square feet of living space, a 3-ton package unit with gas heat, ductwork in the crawl space, and no shade in CZ15. Blower door testing showed the building had envelope air leakage rates indicated in Table 15. The crawl space sealing measure reduced air leakage by about 15%, demonstrating that there was a substantial reduction of conditioned air losses and loads from air transfer with the outside. The crawl space was conditioned by adding a small return duct from the crawl space and three air transfer vents in the floor between the crawl space and living areas.

TABLE 15 - DESERT HOT SPRINGS BLOWER DOOR TESTS

	ENVELOPE LEAKAGE @50 PA (CFM)	ENVELOPE LEAKAGE REDUCTION @50 PA (CFM)	ENVELOPE LEAKAGE (ACH50)	ENVELOPE LEAKAGE REDUCTION (ACH50)
Baseline	1,840	-	15.3	
Conditioned Crawl space	1,560	280 (15%)	13.0	2.3

As seen in Figure 10, the indoor temperatures do not follow the same trend during the baseline and crawl space measure periods. The figure shows that IAT was much cooler during the crawl space measure period, especially at higher ambient temperatures. Note that the IAT was measured close to the ceiling to remain inconspicuous. Thus, the values are useful for normalization and regression analysis, but do not necessarily represent comfort conditions felt by the occupants. Under perfect experimental controls, IAT would remain consistent but occupant behaviors and setpoints were not under control.

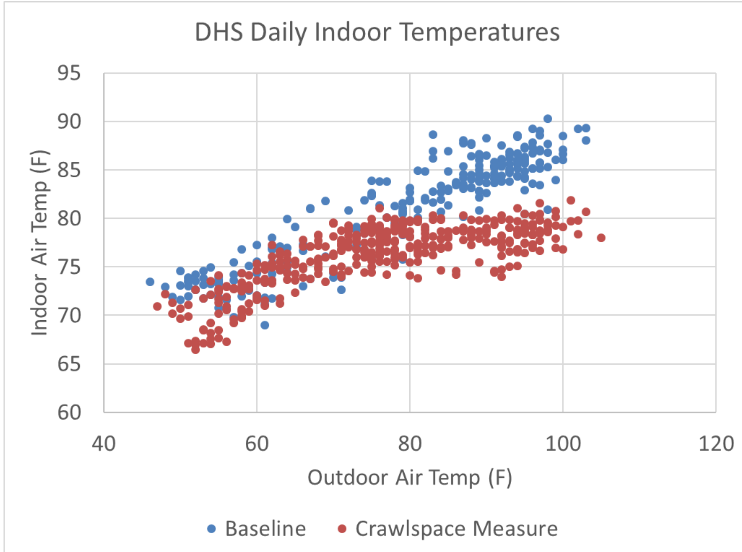

FIGURE 10 - DESERT HOT SPRINGS INDOOR AIR CONDITIONS

The difference in IAT after the measure implementation may be due to a few factors:

- Lower average outside air temperatures during crawl space measure period
- Decreased loads on cooling system (reduction of design point operating hours at or above capacity)
- Changes in thermostat settings or behavior

This decrease in indoor and outdoor air temperatures can also be seen in the psychrometric chart of daily average indoor air conditions in Figure 11. The indoor air data cluster contracts significantly and comfort conditions improve.

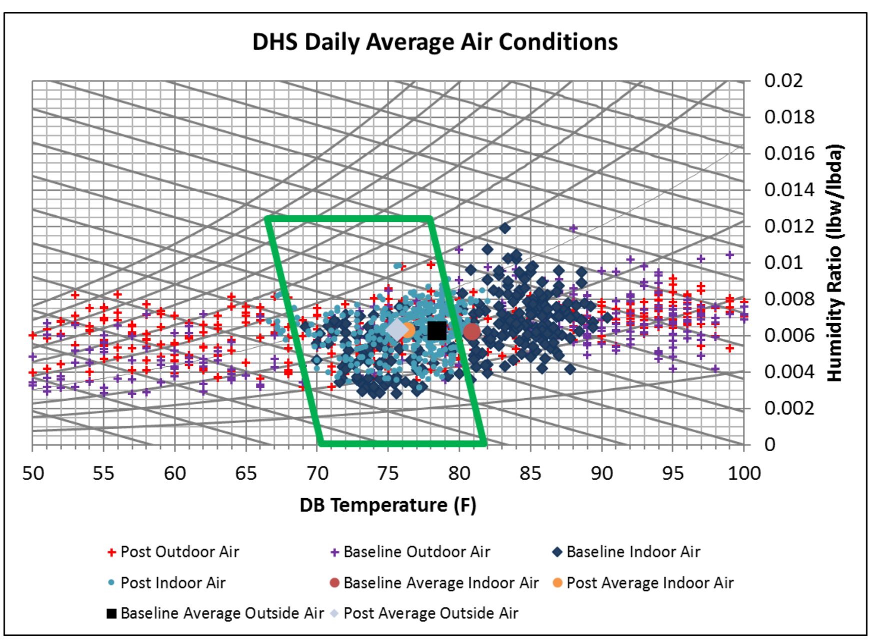

FIGURE 11 – DESERT HOT SPRINGS BASELINE AND CRAWL SPACE MEASURE CASE PSYCHROMETRIC CHART (DAILY AVERAGES)

Normalization of energy use to outdoor and indoor air temperatures can account for these changes between the two periods. For the Desert Hot Springs site, electrical energy use was found to have the most robust relationship to *OAT-IAT*, the difference between inside and outside air conditions. Note that *OAT-IAT* is similar in form to degree days; it is a variable that represents the cooling load of the building based on occupant preferences, outdoor air temperature, and control settings. This choice of independent variables can account for the change in controls and apparent occupant preferences from the baseline to post-crawl space measure period.

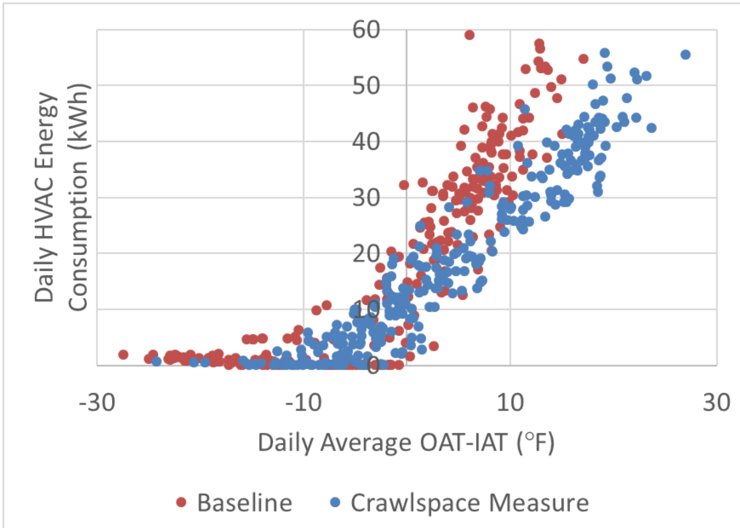

FIGURE 12 – DESERT HOT SPRINGS HVAC ENERGY RELATIONSHIP TO ENVELOPE TEMPERATURE DIFFERENCE

Linear regression models for electrical energy usage were established based on the data shown in Figure 12:

$$Daily\ kWh = \begin{cases} A & for\ all\ OAT < 72 \\ B + C * (OAT - IAT) & for\ all\ OAT \geq 72 \end{cases}$$

The average energy usage outside of the cooling weather was averaged to obtain *C* and the linear regression coefficients are as listed in Table 16.

TABLE 16 – DESERT HOT SPRINGS ELECTRICAL ENERGY REGRESSIONS

	BASELINE	CRAWL SPACE MEASURE
A	1.56	1.16
B	12.64	12.27
C	2.54	1.56
C t-stat	26.3	47.8
C p-value	<0.0001	<0.0001
Regression R^2	0.80	0.90

Additionally, since the indoor temperature patterns changed after the crawl space measure, normalization of IAT was needed. When defined as IAT=f(OAT) from the crawl space measure period, comfort conditions can be modeled as consistent across baseline and measure periods. The indoor air conditions during the post-measure period were selected because they followed a pattern more typical to standard thermostat setpoints than the baseline period.

Figure 13 shows that IAT can be modeled with the following equation.

$$IAT = \begin{cases} 0.38 * OAT + 50.13 & for\ all\ OAT \leq 70 \\ 0.0531 * OAT + 73.404 & for\ all\ OAT > 70 \end{cases}$$

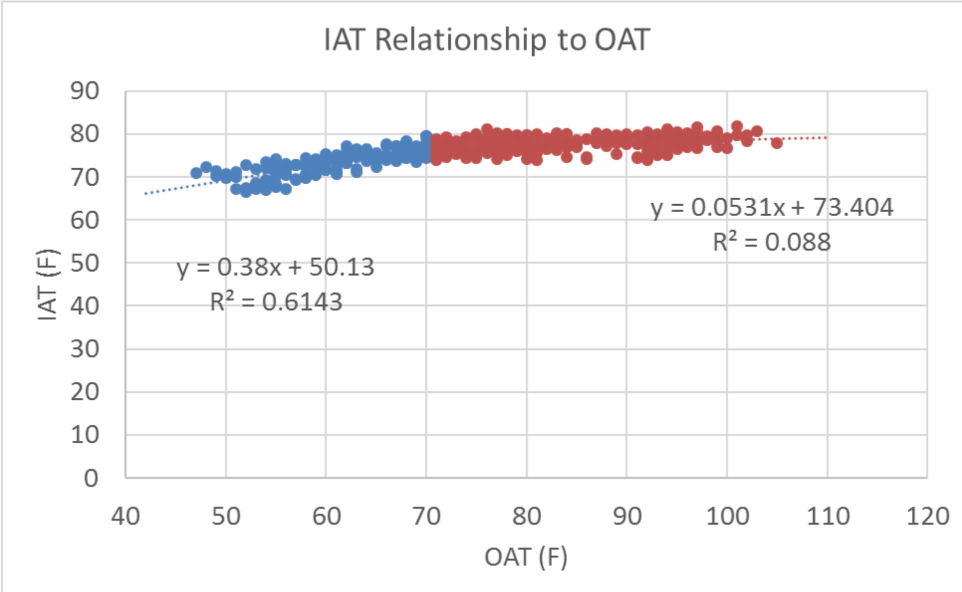

FIGURE 13 - DESERT HOT SPRINGS INDOOR TEMPERATURE AS A FUNCTION OF OAT DURING BASELINE

Similarly, linear regressions for gas consumption can allow for normalized annual energy usage and savings estimates. Gas data was collected from billing statements, so the measurement intervals were about 30 days and were for the whole building rather than space heating only. To account for the varying billing period lengths, weighted linear regression methods were used to avoid bias due to longer intervals.

As shown in Figure 14 and Figure 15, gas usage has an obvious linear relationship to OAT with a changepoint of 75°F.

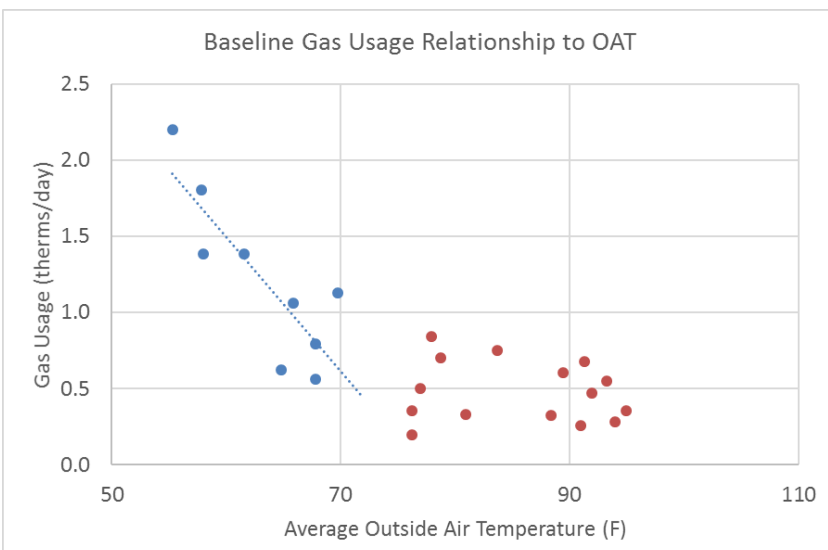

FIGURE 14 – DESERT HOT SPRINGS BASELINE GAS ENERGY USAGE RELATIONSHIP TO OAT

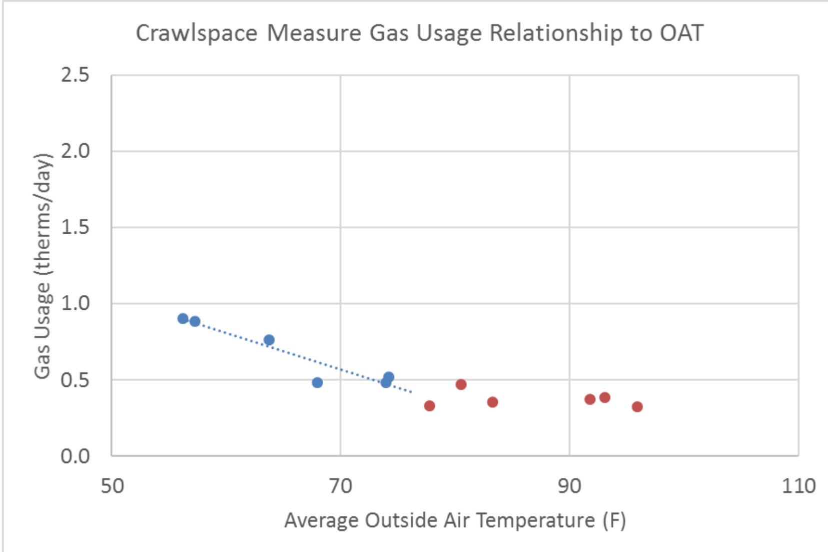

FIGURE 15 – DESERT HOT SPRINGS MEASURE GAS USAGE RELATIONSHIP TO OAT

Weighted linear regressions to average billing period OAT were established in the following form:

$$Daily\ therms = \begin{cases} A & for\ all\ OAT > 75 \\ B + C * OAT & for\ all\ OAT \leq 75 \end{cases}$$

A can be thought of as the average daily gas usage of appliances not including space conditioning.

TABLE 17 - DESERT HOT SPRINGS NATURAL GAS ENERGY REGRESSIONS

	BASELINE	CRAWL SPACE MEASURE
A	0.48	0.37
B	6.9	2.2
C	-0.090	-0.024
C t-stat	2.4	-5.7
C p-value	0.036	0.004
Regression R^2	0.77	0.89

To correct for differences in non-HVAC gas usage, the average daily cooking and water heating gas usage, *A*, was used to correct the annualized gas usage before calculating the gas savings attributable to HVAC usage. In other words, gas savings were calculated as the following.

$$Gas\ Savings = \sum_{i=hour}^{8,760} B_{base} + C_{base} * OAT_i - \sum_{i=hour}^{8,760} B_{post} + C_{post} * OAT_i - [365 * (A_{base} - A_{post})]$$

Gas energy usage could not be corrected for changes in IAT between measurement periods since IAT was not monitored during the entire baseline period of billing data spanning several years. However, Figure 10 suggests that IAT was relatively consistent between monitored baseline and the measure periods during cold weather and is likely not a significantly confounding factor.

Using these models, annual energy usage for average weather year can be estimated. Since it was observed that the average local weather station daily temperatures differed from California CZ temperatures, energy usage for the host sites was modeled for an average year using local weather station data over the most recent three years. Figure 16 and Figure 17 show the baseline and crawl space measure annual energy use profiles using this local weather data year.

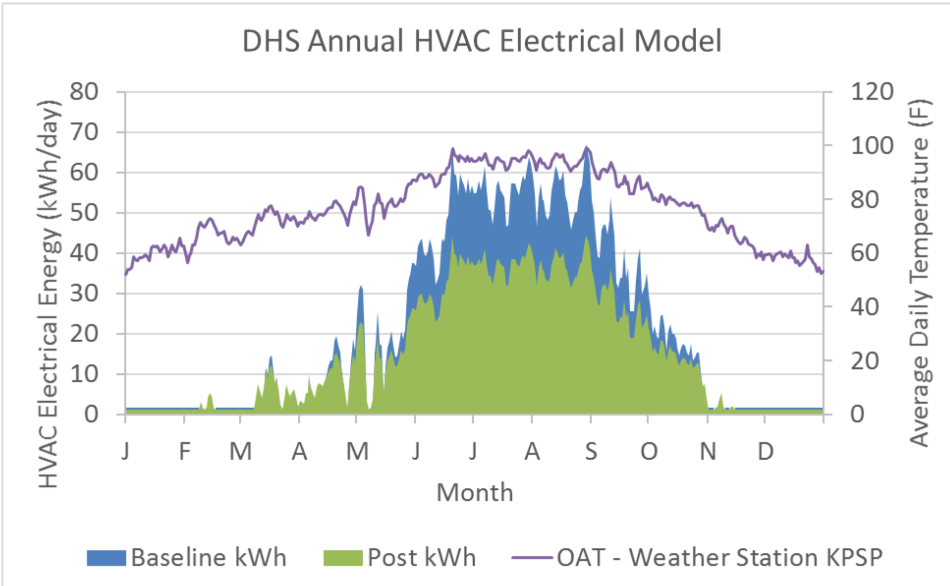

FIGURE 16 – DESERT HOT SPRINGS ANNUAL ELECTRIC USE PROFILE

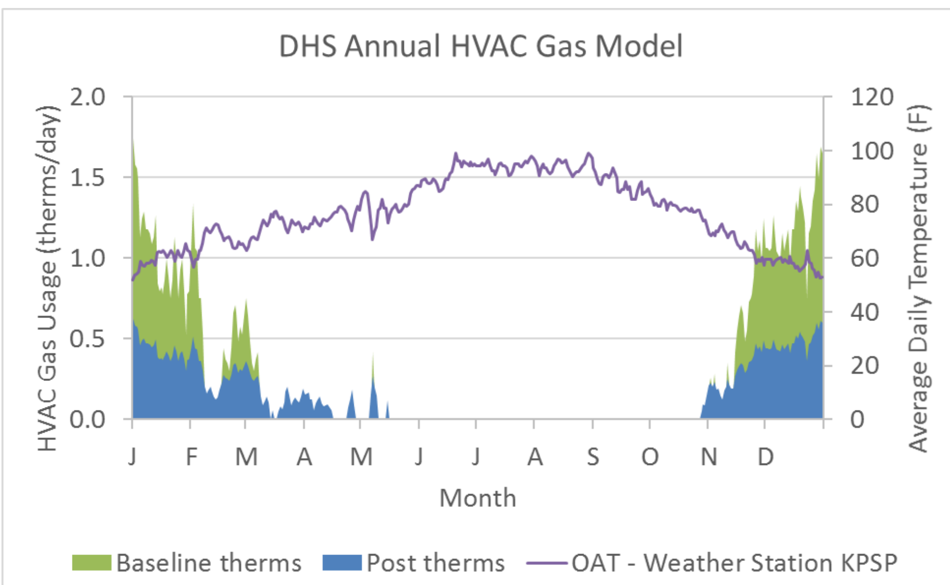

FIGURE 17 - DESERT HOT SPRINGS ANNUAL GAS USAGE PROFILE

Similar calculations using CZ data can be performed to extrapolate the building type to standard California weather years. Table 18 lists the estimated energy usage and savings for each site's CZ and the local weather data for the models established for the Desert Hot Springs building and its occupant behaviors. Usage and savings for the CZ15 host site were multiple times greater for the desert weather patterns. The extreme hot weather of the site may compromise extrapolation to other climate zones. However, the estimated HVAC energy use for the extrapolated climate zones (CZ8, 9, and 10) are within expected HVAC end-use consumption (KEMA, 2010).

TABLE 18 - ENERGY USAGE AND SAVINGS FOR DHS BUILDING TYPE IN SCE CLIMATE ZONES

	Baseline Electricity Usage (kWh/yr)	Electricity Savings (kWh/yr)	Natural Gas Usage (therm/yr)	Natural Gas Savings (therm/yr)
Average Local Weather Station	7,695	2,132	94	40
CZ8	764	26	292	156
CZ9	972	13	273	144
CZ10	1,549	199	290	159
CZ15	7,960	2,371	156	82

In addition to energy savings, the installed measures included a DR-capable thermostat. Since these were installed during the crawl space retrofits, no baseline DR tests were conducted. However, several DR tests during the measure phase were conducted to characterize the DR potential and whether the crawl space and attic sealing and conditioning showed any obvious DR benefit such as increased demand reduction or increased thermal inertia to maintain comfortable inside temperatures over the event.

During the event, thermostat cooling setpoints were increased by 1°F per hour for three hours starting at 2 PM. Demand curves from an adjusted 10-in-10 baseline and the event day showed an obvious demand reduction and an obvious increase in inside temperatures as seen in Figure 18 and Figure 19. The IAT sensor was not located at the thermostat but rather nearer to the ceiling to remain hidden. Thus, Figure 19 shows that inside temperatures increased several degrees but not necessarily what was felt by the occupants.

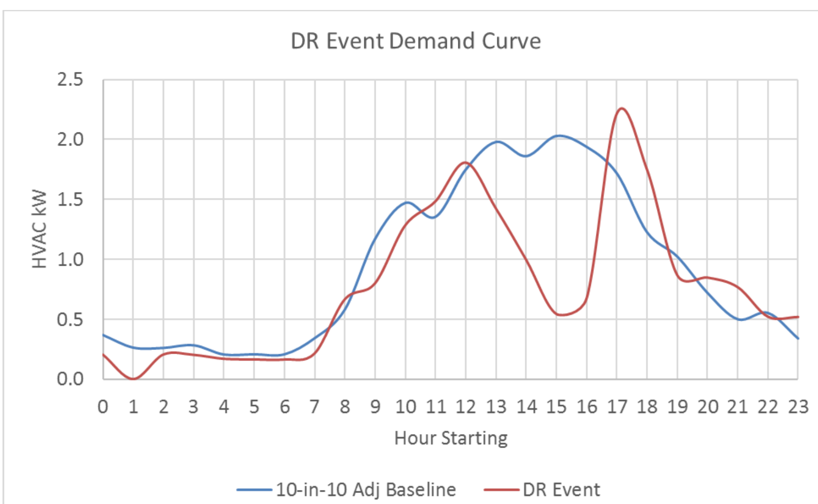

FIGURE 18 – DESERT HOT SPRINGS DR TEST EXAMPLE

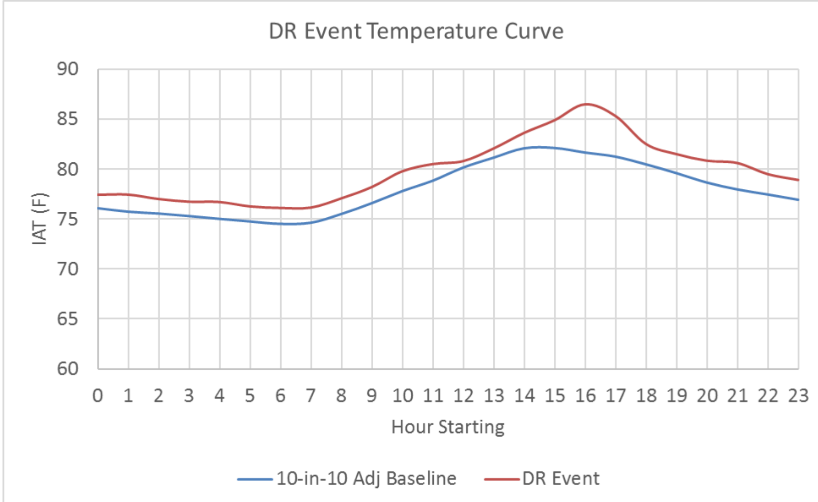

FIGURE 19 – DESERT HOT SPRINGS DR TEST EXAMPLE

Table 19 shows the hourly-averaged DR test results for the hours between 2-5PM, showing an average demand reduction of about 1.14 kW during the peak timeframe.

TABLE 19 – DESERT HOT SPRINGS DR TESTING – CRAWL SPACE MEASURE PHASE

	10-IN-10 UNADJUSTED BASELINE (AVERAGE KW)	10-IN-10 ADJUSTED BASELINE (AVERAGE KW)	UNADJUSTED DEMAND REDUCTION (KW)	ADJUSTED DEMAND REDUCTION (KW)
Test 1	1.60	1.92	0.47	0.82
Test 2	1.51	1.81	1.11	1.41
Test 3	1.75	1.95	1.01	1.20
Average	1.62	1.89	0.86	1.14

SPLIT SYSTEM WITH GAS HEAT - FULLERTON

The Fullerton site is a 1957 single-story building in CZ8 with 1,220 square feet of living space, a 3-ton split system with gas heat, centrally located air handler, and attic ductwork. Blower door testing showed the building had envelope air leakage rates indicated in Table 20.

TABLE 20 - FULLERTON BLOWER DOOR TESTS

	ENVELOPE LEAKAGE @50 PA (CFM)	ENVELOPE LEAKAGE REDUCTION @50 PA (CFM)	ENVELOPE LEAKAGE (ACH50)	ENVELOPE LEAKAGE REDUCTION (ACH50)
Baseline	2,145		13.2	
Conditioned Crawl Space	2,755	-605 (-28%)[9]	16.9	-3.7

The crawl space measure appeared to show a decrease in building air tightness. However, later testing showed no overall, net air tightness change suggesting that the measurement was an error or most of the leakage was through the attic. The

[9] May have been error in post measure reading since energy usage improved and later measurements after work in attic showed no net change in tightness.

crawl space measure included adding a hole in the air handler return pedestal down into the crawl space. This resulted in air circulation between the living space and the crawl space via floor transfer registers.

As seen in Figure 20 and Figure 21, the indoor temperatures have a slightly different relationship to OAT during the baseline and crawl space measure periods, although not as divergent as the Desert Hot Springs site.

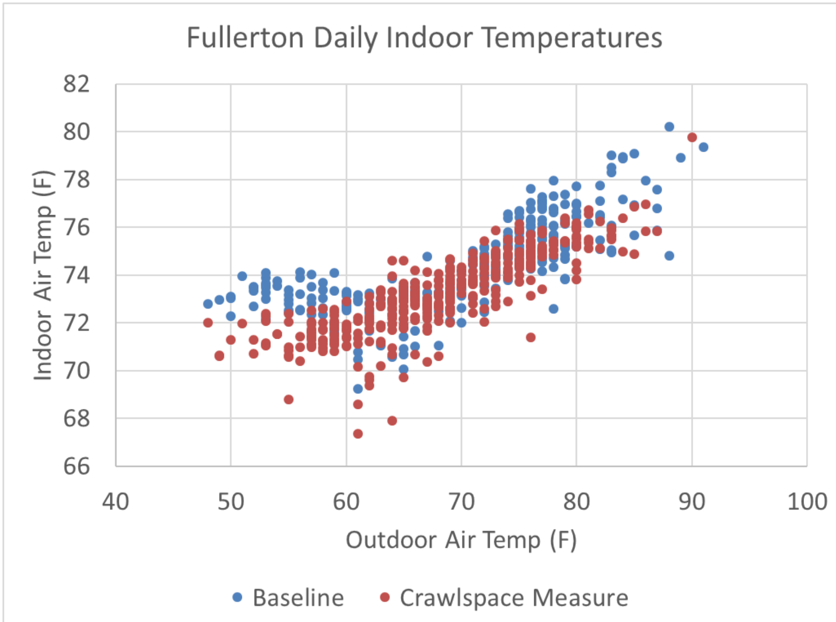

FIGURE 20 – FULLERTON INDOOR AIR TEMPERATURE CONDITIONS

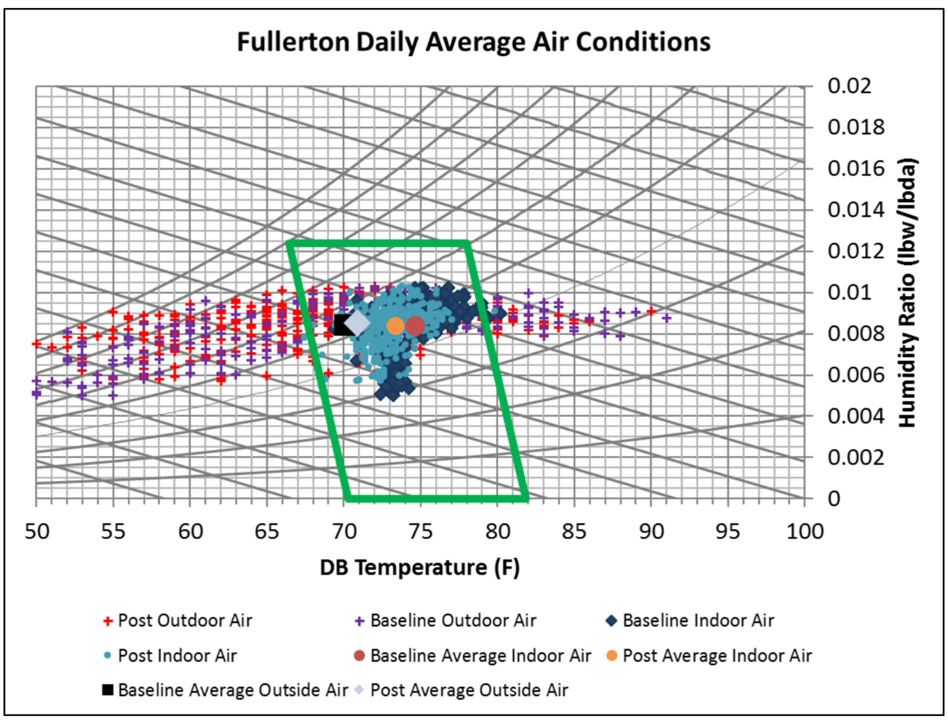

FIGURE 21 – FULLERTON BASELINE AND CRAWL SPACE MEASURE CASE PSYCHROMETRIC CHART (DAILY AVERAGES)

Normalization of energy use to outdoor and indoor air temperatures can account for these changes between the two periods. For the Fullerton site, electrical energy use was found to have the most robust relationship to *OAT* and *IAT.*

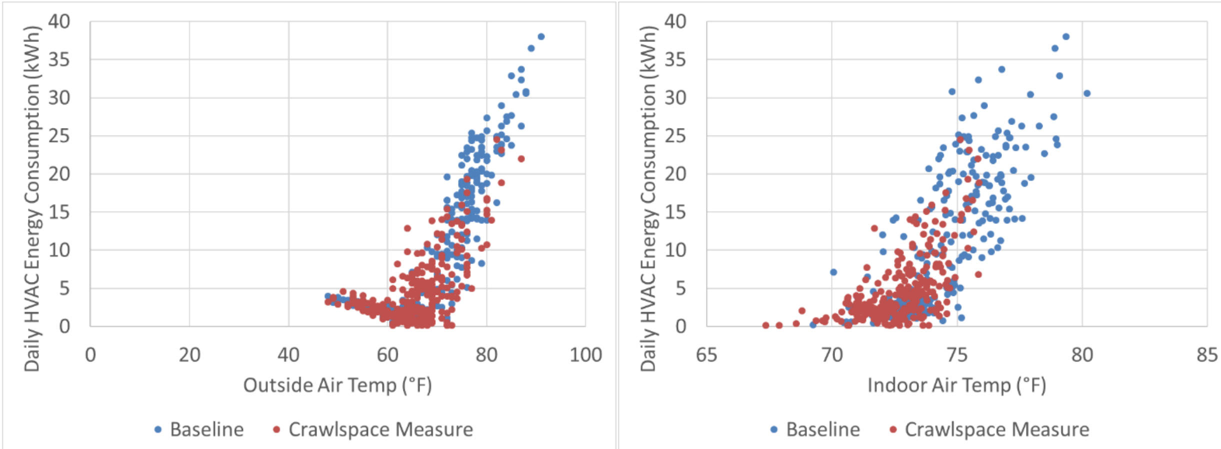

FIGURE 22 – FULLERTON HVAC ENERGY RELATIONSHIP TO OAT AND IAT

Linear regression models for electrical energy usage were established based on the data shown in Figure 22:

$$Daily\ kWh = \begin{cases} A_1 + B_1 * OAT + C_1 * IAT & for\ all < 62 \\ A_2 + B_2 * OAT + C_2 * IAT & for\ all\ \geq 62 \end{cases}$$

TABLE 21 – FULLERTON ELECTRICAL ENERGY REGRESSIONS

	BASELINE		CRAWL SPACE MEASURE	
	For all OAT<62	For all OAT≥62	For all OAT<62	For all OAT≥62
A	-8.75	-90.76	-8.83	-103.37
B	-0.17	1.25	-0.19	0.53
B t-stat	-12.1	15.5	-9.9	8.3
B p-value	<0.0001	<0.0001	<0.0001	<0.0001
C	0.29	0.16	0.31	0.99
C t-stat	4.9	0.57	4.5	3.9
C p-value	<0.0001	0.57	<0.0001	0.0001
R^2	0.81	0.79	0.62	0.54

Additionally, indoor temperature must be established as an independent variable for a normalized comparison. When defined as IAT=f(OAT) from the post period, comfort conditions during the post period can be modeled as the same as the baseline. Figure 23 shows that IAT can be modeled with the following equation.

$$IAT = 131.392 - 2.813 * OAT + 0.042 * OAT^2 - 0.0002 * OAT^3$$

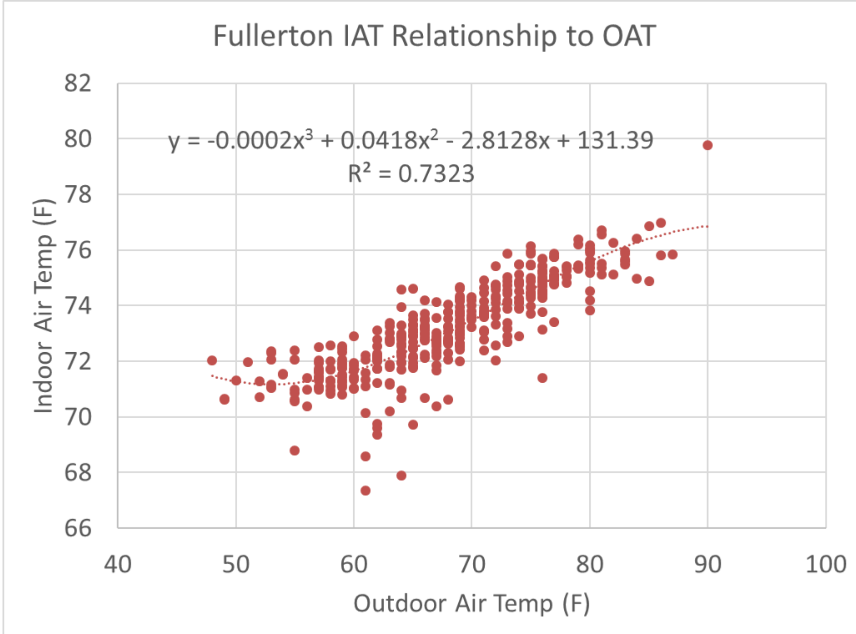

Figure 23 - Fullerton IAT as a Function of OAT during Crawl space Measure Period

Similarly, linear regressions for gas usage can allow for normalized annual energy and savings estimates. Gas data was collected from billing statements, so the measurement intervals were about 30 days and were for the whole building rather than space heating only. To account for the varying billing period lengths, weighted linear regression methods were used to avoid bias due to longer intervals.

As shown in Figure 24 and Figure 25, gas usage has an obvious linear relationship to OAT with a changepoint around 68°F.

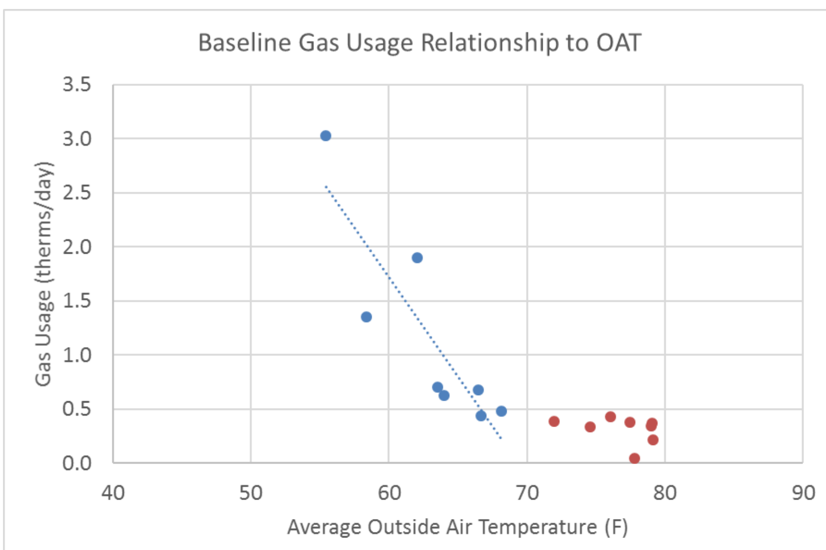

Figure 24 – Fullerton Baseline Gas Usage Relationship to OAT

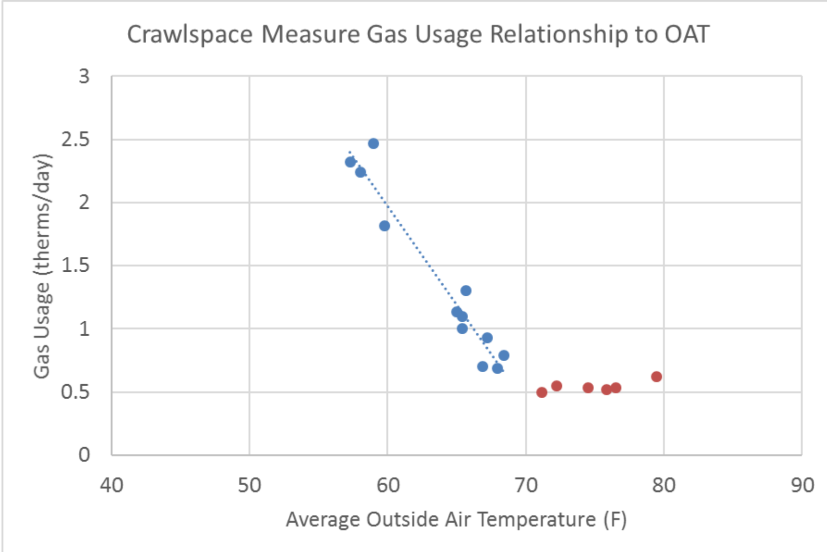

FIGURE 25 – FULLERTON MEASURE GAS USAGE RELATIONSHIP TO OAT

Weighted linear regressions to average billing period OAT were established in the following form:

$$Daily\ therms = \begin{cases} A & for\ all\ OAT > 68 \\ B + C * OAT & for\ all\ OAT \leq 68 \end{cases}$$

TABLE 22 - FULLERTON NATURAL GAS ENERGY REGRESSIONS

	BASELINE	CRAWL SPACE MEASURE
A	0.33	0.54
B	12.8	11.4
C	-0.18	-0.16
C t-stat	2.44	4.84
C p-value	0.050	0.0007
Regression R^2	0.79	0.93

To correct for differences in non-HVAC gas usage, the average daily cooking and water heating gas usage, *A*, was used to correct the annualized gas usage before calculating the gas savings attributable to HVAC usage.

Gas energy usage could not be corrected for changes in IAT between measurement periods since IAT was not monitored during the entire baseline period of billing data spanning several years.

Using these models, the annual energy usage for average host site weather year can be calculated. Since it was observed that the average local weather station daily temperatures differed from California climate zone temperatures, energy usage for the host sites was modeled for an average weather year based on the local weather station over the most recent three years.

Figure 26 and Figure 27 show the baseline and crawl space measure annual energy use profiles using the average local weather data.

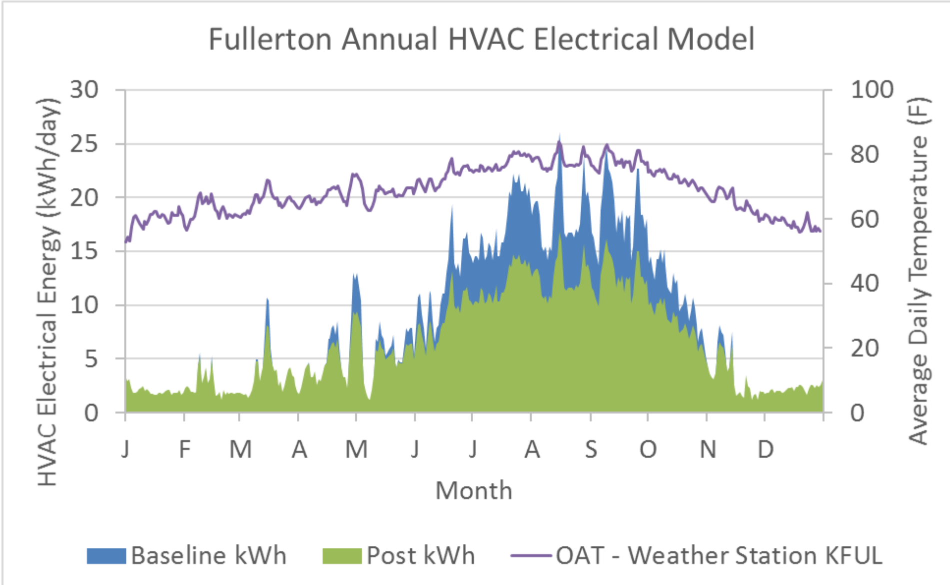

FIGURE 26 – FULLERTON ANNUAL ELECTRIC USE PROFILE

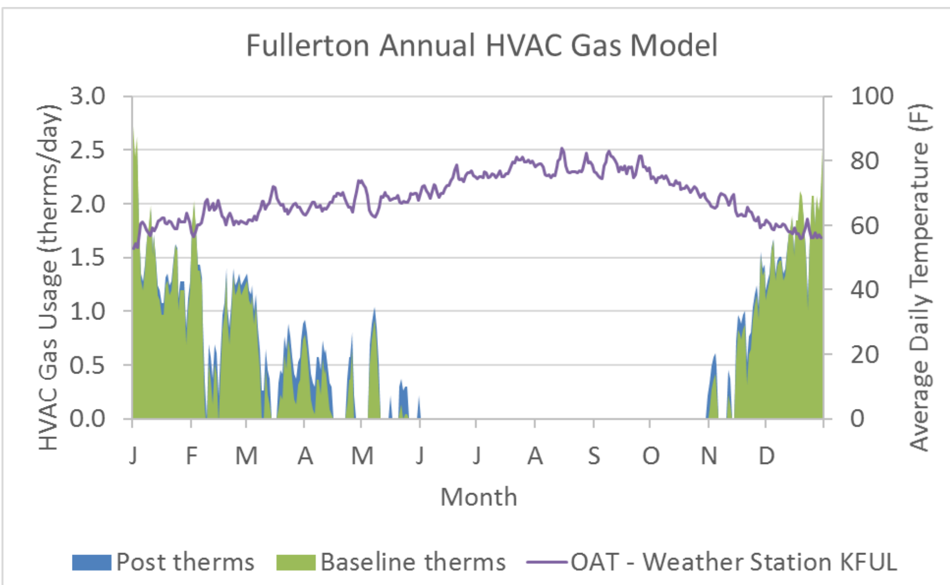

FIGURE 27 - FULLERTON ANNUAL GAS USAGE PROFILE

Similar calculations using CZ data can be performed to extrapolate the building type to standard California weather years. Table 23 lists the estimated energy usage and savings for each site's CZ and the local weather data for the models established for the Fullerton building and its occupant behaviors.

TABLE 23 - ENERGY USAGE AND SAVINGS FOR FULLERTON BUILDING TYPE IN SCE CLIMATE ZONES

	BASELINE ELECTRICITY USAGE (KWH/YR)	ELECTRICITY SAVINGS (KWH/YR)	NATURAL GAS USAGE (THERM/YR)	NATURAL GAS SAVINGS (THERM/YR)
Average Local Weather Station	2,996	625	397	-10
CZ8	1,532	33	164	-20
CZ9	1,811	166	383	-8
CZ10	2,285	326	434	2
CZ15	6,464	2,267	229	-5

An average hourly energy profile could be made for the Fullerton site as seen in Figure 28. It shows that energy savings are evenly distributed over the day in the summer, especially during daytime hours.

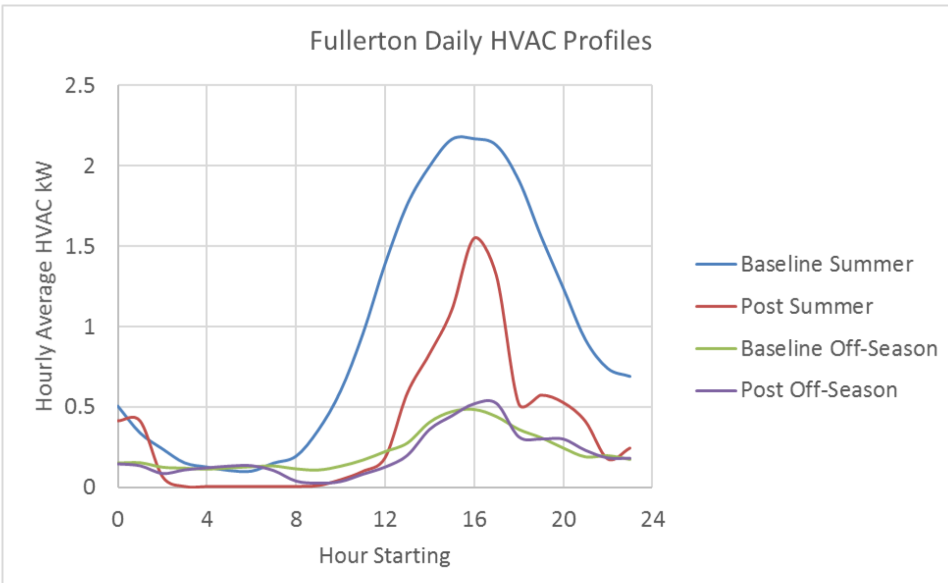

FIGURE 28 – DAILY DEMAND PROFILE FOR FULLERTON SITE

In addition to energy savings, the installed measures included a DR-capable thermostat. Since these were installed during the crawl space retrofits, no baseline DR tests were conducted. However, several DR tests during the measure phase were conducted to characterize the DR potential and whether the crawl space and attic sealing and conditioned showed any obvious DR benefit such as increased demand reduction or increased thermal inertia to maintain comfortable inside temperatures over the event.

During the event, thermostat cooling setpoints were increased by 1°F per hour for three hours starting at 2 PM. Demand curves from an adjusted 10-in-10 baseline and the event day showed an obvious demand reduction and an obvious increase in inside temperatures as seen in Figure 29 and Figure 30. The IAT sensor was not located at the thermostat but rather nearer to the ceiling to remain hidden. Thus, Figure 30 shows that inside temperatures increased several degrees but not necessarily what was felt by the occupants.

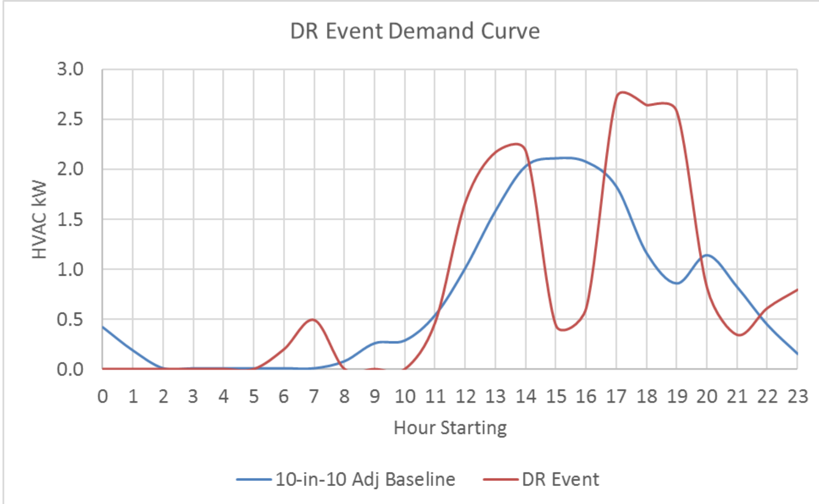

Figure 29 – Fullerton DR Test Example

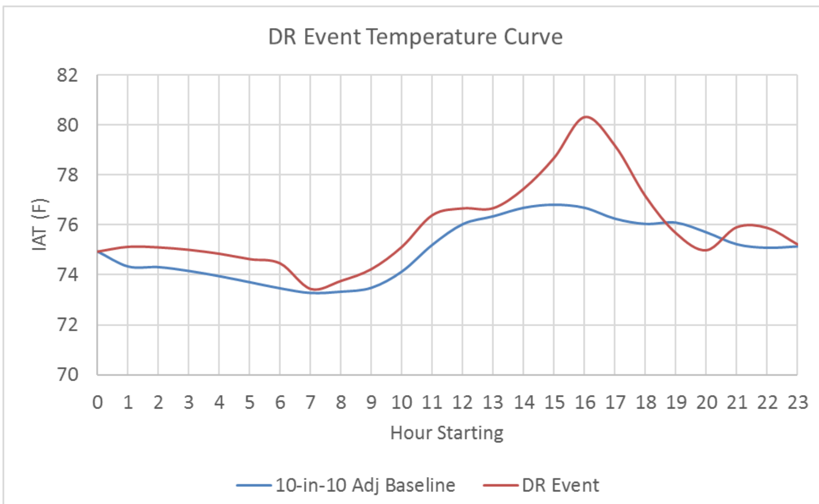

Figure 30 – Fullerton DR Test Example

Table 24 shows the hourly-averaged DR test results for the hours between 2-5PM, showing an average demand reduction of about 0.95 kW during the peak timeframe.

Table 24 – Fullerton DR Testing – Crawl space Measure Phase

	10-in-10 Unadjusted Baseline (Average kW)	10-in-10 Adjusted Baseline (Average kW)	Unadjusted Demand Reduction (kW)	Adjusted Demand Reduction (kW)
Test 1	1.46	1.75	0.60	0.89
Test 2	1.73	2.08	0.65	1.00
Average	1.62	1.95	0.63	0.95

Supplemented Packaged Heat Pump - Murrieta

The Murrieta site is a 1980 two-story building with 2,440 square feet of living space (1,500 first floor and 940 second floor). The residence is conditioned by a 30,000

Btu/h heat pump with crawl space ductwork to the first floor, two 5,000 Btu/h window units on the second floor, and a whole house fan in the attic. A second heat pump used to serve the second story but has been out of service for years and has been replaced by the window units. The vented crawl space already had a vapor barrier on the ground before the study began.

Blower door testing showed the building had envelope air leakage rates indicated in Table 25. The crawl space sealing measure improved building air tightness by about 8%.

TABLE 25 - MURRIETA BLOWER DOOR TESTS

	ENVELOPE LEAKAGE @50 PA (CFM)	ENVELOPE LEAKAGE REDUCTION @50 PA (CFM)	ENVELOPE LEAKAGE (ACH50)	ENVELOPE LEAKAGE REDUCTION (ACH50)
Baseline	5,025		13.7	
Conditioned Crawl space	4,615	410 (8%)	12.6	1.1

As seen in Figure 31, the overall average indoor and outdoor temperatures for the measurement periods shifted warmer. However, this is likely to due to a measurement gap during the baseline summer months from instrumentation error, especially for the shift in average OAT.

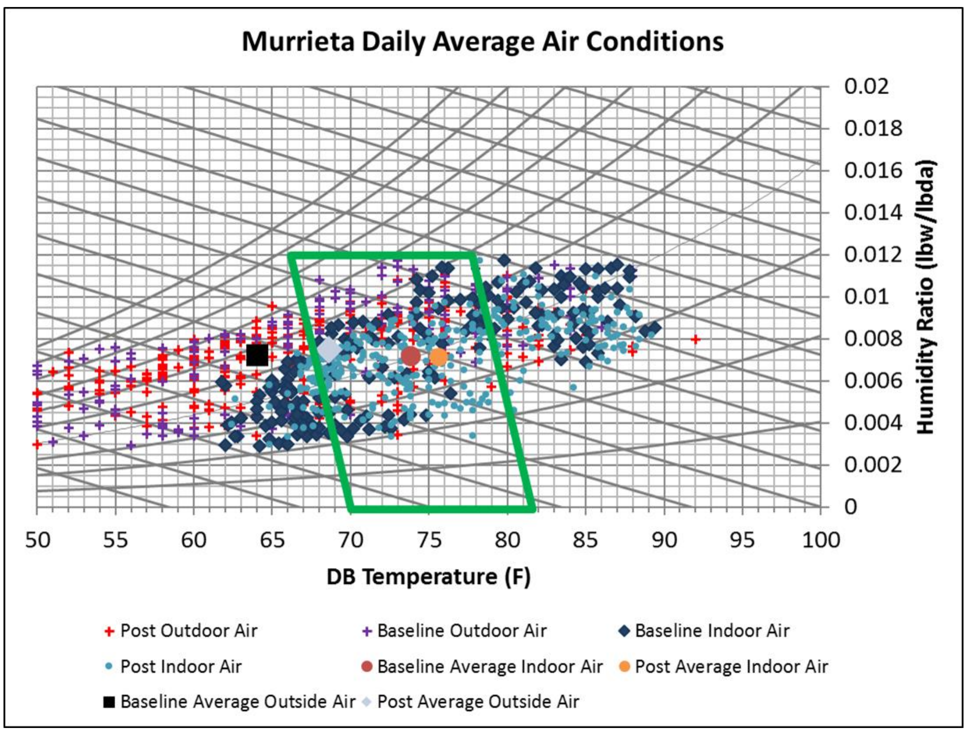

FIGURE 31 – MURRIETA BASELINE AND CRAWL SPACE MEASURE CASE PSYCHROMETRIC CHART (DAILY AVERAGES)

For the Murrieta site, electrical energy use was found to have a significant relationship to OAT, OAT^2, and IAT. The quadratic term is a result of the nonlinear relationship between heat pump efficiency (and perhaps occupant preferences) to outside air temperature seen in Figure 32. Other regressions options were tested (piecewise, linear, etc.) but all showed similar results. However, note that the post-measure regression is basically shifted up from the baseline by about 2 kWh per day and the relationship to outside air temperature appears to be largely unchanged.

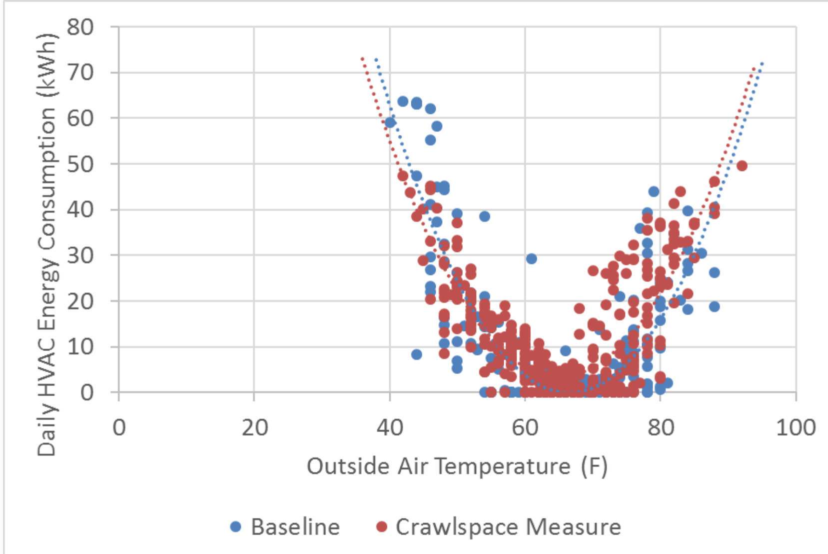

FIGURE 32 – MURRIETA HVAC ENERGY RELATIONSHIP TO OAT

In fact, the difference in normalized energy between the baseline and post-measure conditions were calculated to be just about 750 kWh in CZ10. Thus, based on this uncertainty in normalized savings and stark similarity between the baseline and post-measure case regressions, there was little evidence that the measure significantly affected energy consumption. Despite this, the regression analysis that was performed can be found in Appendix B. The authors conclude that there was little-to-no effect on energy usage at this site, similar to what has been found occasionally by other studies.

The Murrieta site did not yield any usable DR tests. Occupant preferences and thermostat setpoints leading up to the DR events or on during event days showed too infrequent HVAC usage to establish a baseline or event day profile for each test that was performed. Setpoints were frequently found to be 82-95 °F during DR event tests.

WINDOW UNITS - POMONA

The Pomona site is a 1920 single-story building with 1,160-square feet of living space and two window units in CZ9. Blower door testing showed the building had envelope air leakage rates indicated in Table 26. The crawl space sealing did not have much effect on building tightness, suggesting that other parts of the building were more responsible for the high leakage rate.

TABLE 26 - POMONA BLOWER DOOR TESTS

	ENVELOPE LEAKAGE @50 PA (CFM)	ENVELOPE LEAKAGE REDUCTION @50 PA (CFM)	ENVELOPE LEAKAGE (ACH50)	ENVELOPE LEAKAGE REDUCTION (ACH50)
Baseline	5,810		37.6	
Conditioned Crawl Space	5,735	73 (1%)	37.1	0.5

As seen in Figure 33 and Figure 34, the indoor temperatures follow the same trend during the baseline and crawl space measure periods. In Figure 34, the change in overall average OAT is driven by a data collection gap during the baseline summer months. Based on the similar IAT trends across measurement periods and the insignificant relationship between energy consumption and IAT, no normalization of IAT in the energy modeling was necessary as it was for the other sites.

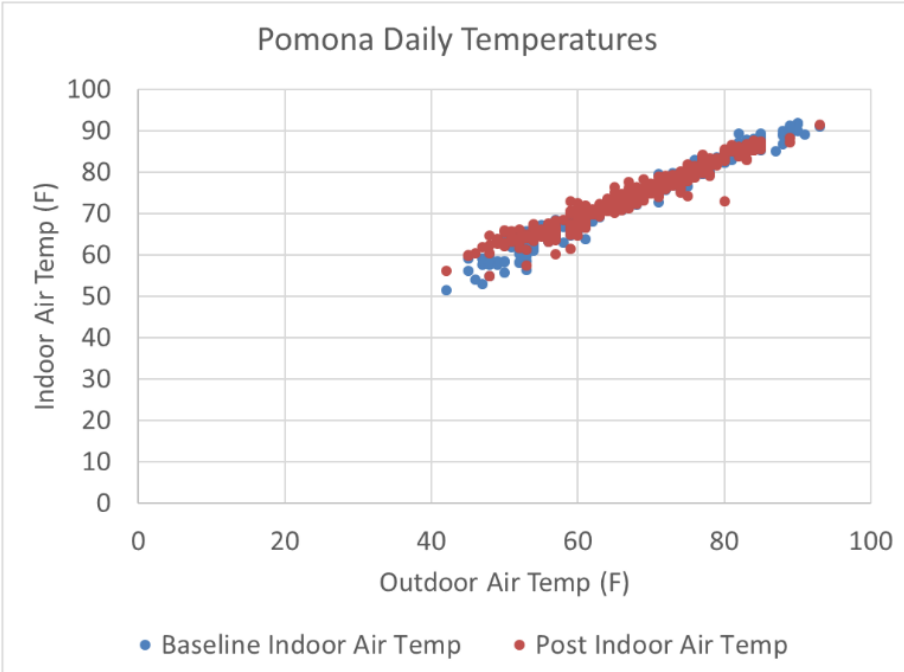

Figure 33 - Pomona Indoor Air Conditions

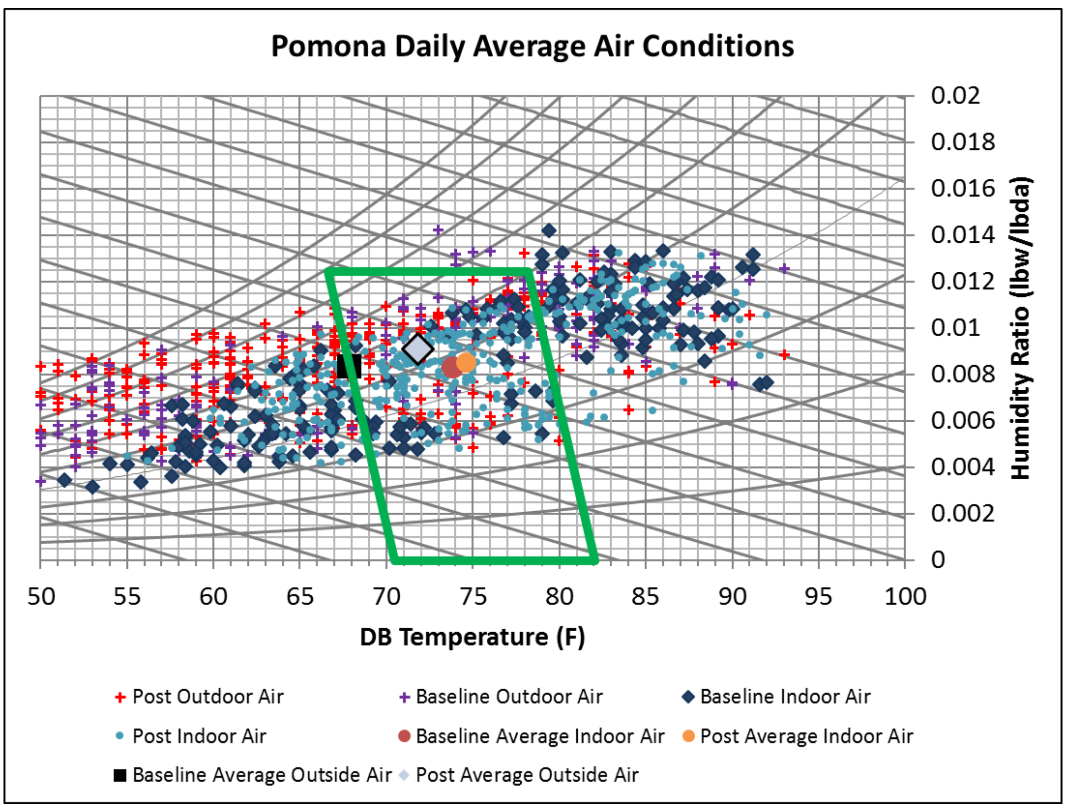

Figure 34 – Pomona Baseline and Crawl space Measure Case Psychrometric Chart (Daily Averages)

For the Pomona site, electrical energy use was found to have the most robust relationship to cooling degree days (CDD) with a base of 85. This variable was found to be more robust than OAT can account for occupant comfort preferences more readily than average daily OAT. This is an unusually high base temperature, but the window unit usage patterns confirm that the occupants rarely used cooling and only at high temperatures.

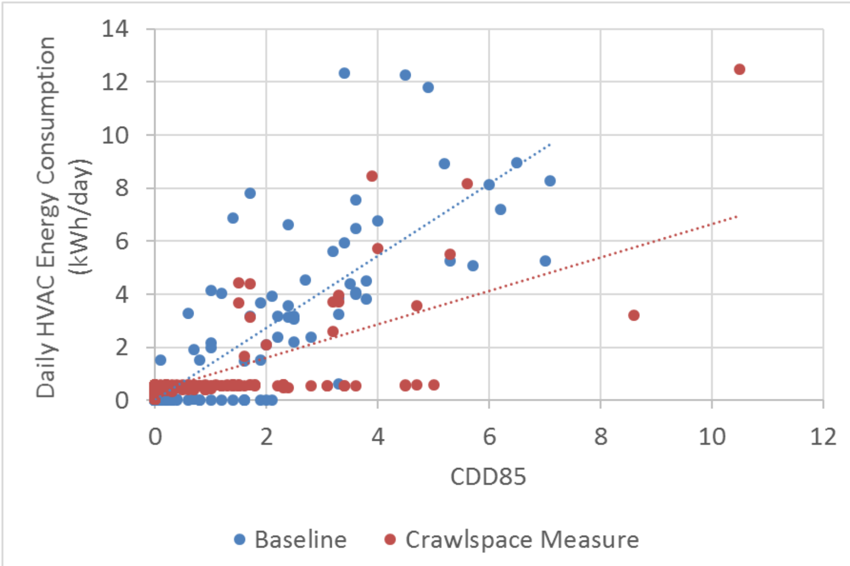

FIGURE 35 – POMONA HVAC ENERGY RELATIONSHIP TO CDD85

Linear regression models for electrical energy usage were established based on the data shown in Figure 35.

$$Daily\ kWh = A + B * CDD85$$

A ducted fan was installed to transfer air between the crawl space and living space to generate circulation through the two spaces. Note that the difference between A for the baseline and crawl space measure periods is roughly equivalent to the daily energy consumption of the transfer fan when cooling is not typically needed.

TABLE 27 – POMONA ELECTRICAL ENERGY REGRESSIONS

	BASELINE	CRAWL SPACE MEASURE
A	0.028	0.341
B	1.354	0.632
B t-stat	22.9	17.9
B p-value	<0.0001	<0.0001
Regression R^2	0.72	0.49

Figure 36 shows the baseline and crawl space measure annual energy use profiles using the average local weather data.

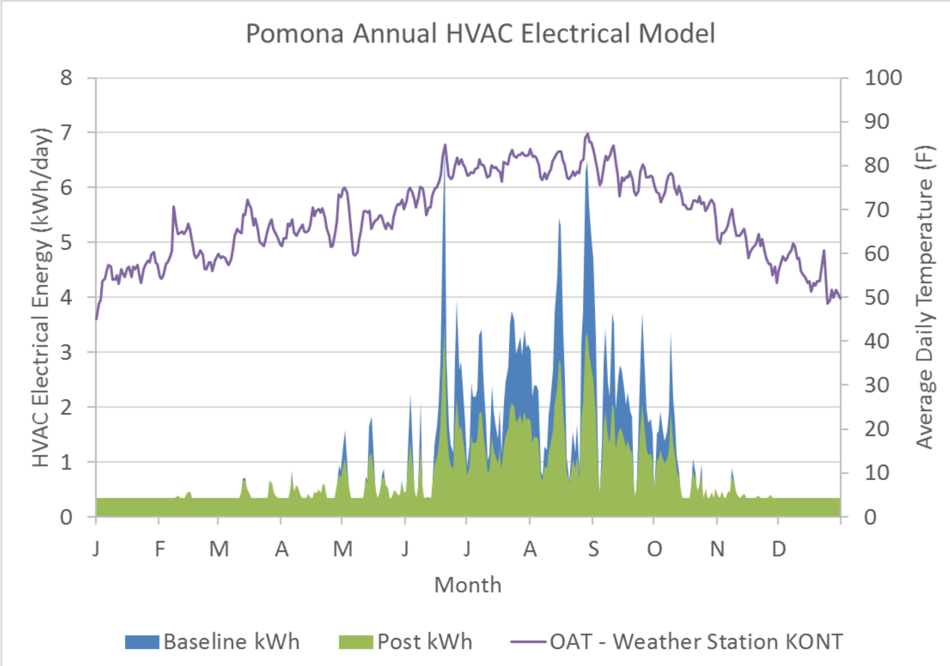

FIGURE 36 – POMONA ANNUAL ELECTRIC USE PROFILE

Similar calculations using CZ data can be performed to extrapolate the building type to standard California weather years. Table 18 lists the estimated energy usage and savings for each SCE climate zone and the local weather data for the models established for the Pomona building type and its occupant behaviors.

TABLE 28 - ENERGY USAGE AND SAVINGS FOR POMONA BUILDING TYPE IN SCE CLIMATE ZONES

	BASELINE ELECTRICITY USAGE (KWH/YR)	ELECTRICITY SAVINGS (KWH/YR)
Average Local Weather Station	344.4	64.1
CZ8	50.0	-92.9
CZ9	144.6	-42.4
CZ10	303.1	42.1
CZ15	1,777.6	828.5

However, the crawl space measure period energy consumption is partially driven by the forced transfer fan that was installed to circulate air between the crawl space and living space. The fan was controlled by the installed PCT, but was not set optimally. As seen in Figure 37, the fan ran almost constantly during the heating season (when average OAT is less than 60, for instance). Since the crawl space air transfer would most likely be a benefit during the cooling season and a penalty during heating season, there is little reason to circulate cooler air from the crawl space during the heating season except to maintain moisture levels. A more efficient fan or controls could potentially reduce this energy penalty.

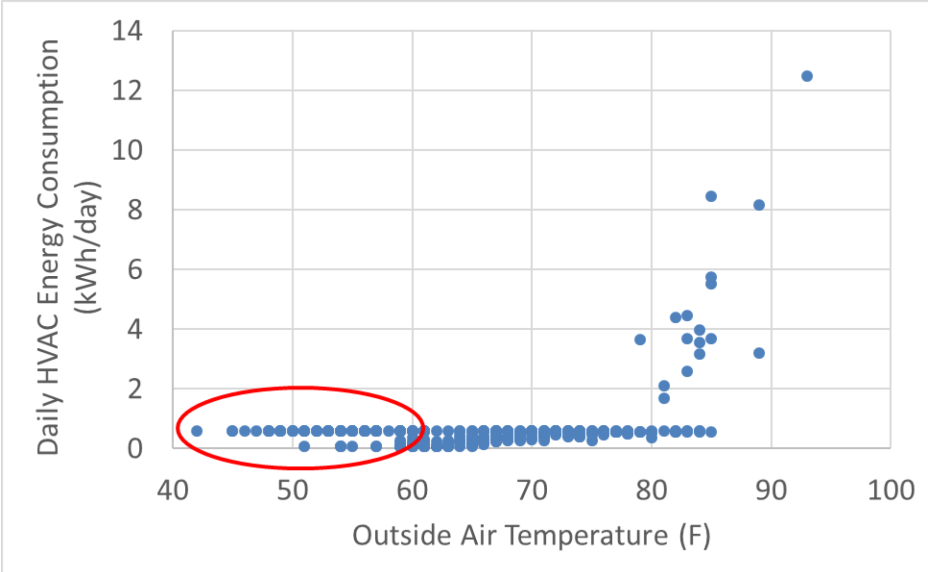

FIGURE 37 – POMONA CRAWL SPACE MEASURE PERIOD DAILY KWH OVER OAT SHOWING SUBOPTIMAL TRANSFER FAN OPERATION

By that reasoning, the fan should have been turned off when average daily OAT was less than 60°F as long as humidity levels remained low. If that were true, then the energy usage and savings would change to those listed in Table 29. Generally, energy usage and savings are low because the occupants had an unusually large comfort zone and the cooling equipment was rarely used.

TABLE 29 – ENERGY USAGE AND SAVINGS FOR POMONA BUILDING TYPE CORRECTED FOR PROPER TRANSFER FAN CONTROL

	BASELINE ELECTRICITY USAGE (KWH/YR)	ELECTRICITY SAVINGS (KWH/YR)
Average Local Weather Station	344.4	91.0
CZ8	50.0	-46.6
CZ9	144.6	-15.6
CZ10	303.1	86.2
CZ15	1,777.6	852.0

The Pomona site did not have any DR capabilities since the window units could not be controlled by a PCT or other DR-enabled controls.

DISCUSSION AND CONCLUSIONS

The field assessment of conditioned, sealed crawl spaces under differing conditions produced a variety of results. Four sites were monitored for three seasons under existing baseline conditions and one year after a conditioned crawl space retrofit. Normalized energy savings were calculated for each site and extrapolated to the other participating climate zones for comparison. Indoor air quality was observed and DR tests were performed during the measure period. The market size, potential savings, and barriers were studied. The measure is particularly useful for homes with ductwork in the crawl space, high envelope leakage, high duct leakage, excessive crawl space venting, and homes with high HVAC energy usage. Baseline conditions without vapor barriers already installed would see more savings.

Two sites were much better test cases with better experimental control and representative conditions. The Fullerton and Desert Hot Springs sites had more consistent use patterns and robust regressions than the other sites. These two sites showed annual HVAC electric savings of about 21 and 28% and whole building electric EUI savings of 10% and 18%. These savings are similar to those found in previous studies. One site showed natural gas savings of 42% while another showed an increase in gas usage of 12%. This mixed result on heating energy usage was not unexpected and has been observed in another study; however, controls may be able to mitigate heating energy penalties in advanced applications. The best results were found for the building in the hottest climate zone and with ducting in the crawl space.

The other two sites had some confounding test conditions and may not have been entirely representative of typical buildings or conditions that should be targeted for this measure. The Murrieta site showed inconclusive results and may suggest that both the baseline and measure used about the same amount of energy. This site was confounded by a baseline that had a vapor barrier already installed and unusual occupant setpoint preferences (setpoints were observed to often be greater than 85 °F in the summer during unoccupied times). The Pomona site with only two small window units showed 19% electrical energy savings and an overall EUI reduction of 1%. Although energy savings were observed at this site, they were only 91 kWh/year due to the overall low usage of cooling equipment and occupant preferences.

Carbon monoxide and radon levels in the home were not significantly negatively or positively affected and levels basically stayed the same after retrofit and within safety limit recommendations. Humidity levels in the crawl spaces were reduced for all four sites. During the baseline, three of the houses saw RH levels exceed the recommended limit of 70% with regularity. After the sealing, crawl space RH levels were reduced below the recommended limit under all conditions. This confirms previous conclusions that venting is not strictly necessary for moisture control and that sealing with a vapor barrier may work better in most cases.

Comfort conditions improved at all sites. The daily average IAT and RH levels were all closer to the typical ASHRAE comfort zone after the measure implementation. It is not possible to determine whether this was a result of the crawl space sealing or the new thermostats that were installed. It is likely both had a positive effect on comfort levels.

Successful DR simulations were conducted at two of the four sites. These tests were remote adjustments of the thermostat setpoint by 1 degree per hour over three peak summer hours. The two sites showed average, baseline adjusted DR reductions of 0.95 and 1.14 kW, similar to other residential DR testing in other studies (Southern California Edison, 2009).

Unfortunately, the DR-enabled thermostats were not installed in the baseline so there could not be a comparison of the DR potential with and without the measure. The hypothesis is that the added thermal mass and "stored cooling" in the crawl space would allow for more comfortable, reduced compressor cycling DR event. It was observed that IAT increased rapidly during the DR tests and occupants had to be reminded not to adjust the thermostat during the test. The occupants occasionally did manually override the DR test, suggesting that the increase in IAT was excessive for their comfort.

The market size for this retrofit measure for existing homes is roughly 441,600 SFR homes in SCE territory and 1,387,700 across California. These are single family homes with vented, unconditioned crawl spaces. Of these, about 66% and 56% have central air in SCE territory and California, respectively. If the Fullerton and Desert Hot Springs sites are considered typical of these SFR buildings with central air and crawl spaces, the energy savings potential is on the order of 400 and 1,100 GWh/year for SCE territory and California existing homes, respectively.

Those with ductwork in the crawl space should be the primary target of outreach due to the highest energy savings opportunity. The market share of new construction homes with crawl spaces does appear to be decreasing over the last several years, but does not necessarily imply a permanent trend.

The average cost of the measure for the sites was about $8.7 per square foot of crawl space area. Simple payback for the measures at the sites would be over 30 years based on the data collected and the project costs. However, there are several factors that make this measure attractive despite this long payback from energy savings alone:

- Non-energy benefits include reduced risk of dry rot, mold, water, and pests which can add to cost savings and increased building lifespan.

- Non-energy benefits include improved IAQ and health effects such as lessened risk of asthma and potentially radon.

- Costs would likely decrease as service providers became familiar with the measure and competition increased.

- TDV energy and cost savings (not directly seen by the customer) would be very different from the billing savings and would add more societal benefit that the calculated cost savings suggest. The energy savings were concentrated during the cooling season and appear to be well distributed throughout the day so that savings occur during peak hours.

- Payback would likely be better for new construction buildings or if work in the crawl space is already being performed.

- The additional cool air and thermal mass in the crawl space likely marginally increase DR effectiveness but the tests could not quantify this effect.

Since this is a set of construction retrofit measures, there are significant market barriers to adoption. Namely, customer cost is high and potential benefits are not well known. It is unlikely that homeowners would consider sealing and conditioning their crawl spaces when there are competing priorities associated with other home repair and maintenance needs. This resistance could potentially be mitigated through market outreach of the benefits and appropriateness of application, incentives, or leveraging opportunities when homeowners already need to do projects such as rodent-proofing, insulation, moisture or radon mitigation, leak repair, or ducting repair.

No commonly used building modeling software (such as CBECC-Res or eQuest) allows for modeling of sealed, conditioned crawl spaces. This is a market barrier that would have to be addressed, particularly in the new construction market. The other primary barrier, especially in retrofit cases, is limited contractor awareness, familiarity, and expertise (Dastur, Mauceri, & Hannas, 2009). It is difficult to find contractors who are qualified and interested in doing this type of retrofit. Construction guides for conditioned crawl spaces have been published but market adoption and contractor awareness remains low (Advanced Energy, 2005). The measure could be promoted through outreach to contractors and new home builders through workshops and other promotional and training programs. Builders and contractors still sometimes avoid the measure based on the misunderstanding that it is not allowed under code since vented crawl spaces used to be required (Lstiburek, 2004). Ideally, studies such as this one, outreach, promotion, support, and construction guidelines can help spur market adoption.

RECOMMENDATIONS

Based on the promising nature of the measure and variety of benefits, consideration for program support is recommended. Recommended courses of action for furthering market adoption include the following:

- Gather construction and industry professionals for a workshop to identify opportunities for cost reduction and standardization.

- Perform comprehensive building modeling study and sensitivity analysis of building conditions and climate zones to determine optimal building and sub-sector targets for existing or new construction programs.

- Study code change implications since new building costs are lower and TDV savings would likely provide improved payback.

- Any subsequent studies should focus on controlling conditions as much as possible. For instance, any future study should install programmable thermostats with appropriate settings before the baseline. This will allow for baseline DR testing and help avoid changes to occupant behavior due to improved setpoint control. Additionally, occupants should be screened for their HVAC use and setpoint preferences prior to enrollment to avoid unusual cases such as the Murrieta and Pomona sites. Several planned side-by-side, unoccupied, controlled sites for this study were anticipated but could not be included. This type of test site could help maintain control conditions.

- The highest savings building type is older homes with ductwork in vented crawl spaces. Any targeted programs could focus on this building type first.

- Develop custom modeling of buildings with conditioned crawl spaces to inform changes to compliance and whole building software such as CBECC-Res.

- Explore options for optimizing crawl space air flow during heating and cooling seasons. Energy penalties may exist during heating season that could potentially be mitigated by control strategies.

- Potential program support includes code changes, new construction energy budgeting of conditioned crawl space savings, contractor outreach and training, and incentives for retrofits potentially packaged with other measures for overall cost-effectiveness.

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APPENDIX A – LOCAL STATION AND CZ WEATHER DATA

Figure 38 shows the average daily weather conditions used for the normalized annualization the Desert Hot Springs host site. Generally, the average weather station OAT for the site is smoother than the CZ data due to averaging over several years of data.

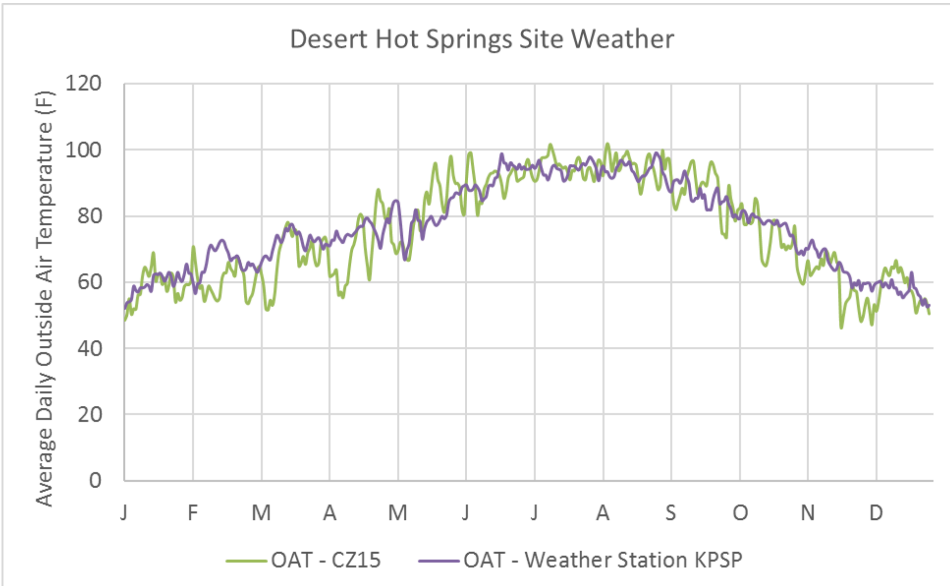

FIGURE 38 – DESERT HOT SPRINGS HOST SITE WEATHER AND CZ15

Figure 39 shows the average daily weather used for the normalized annualization the Fullerton host site energy usage.

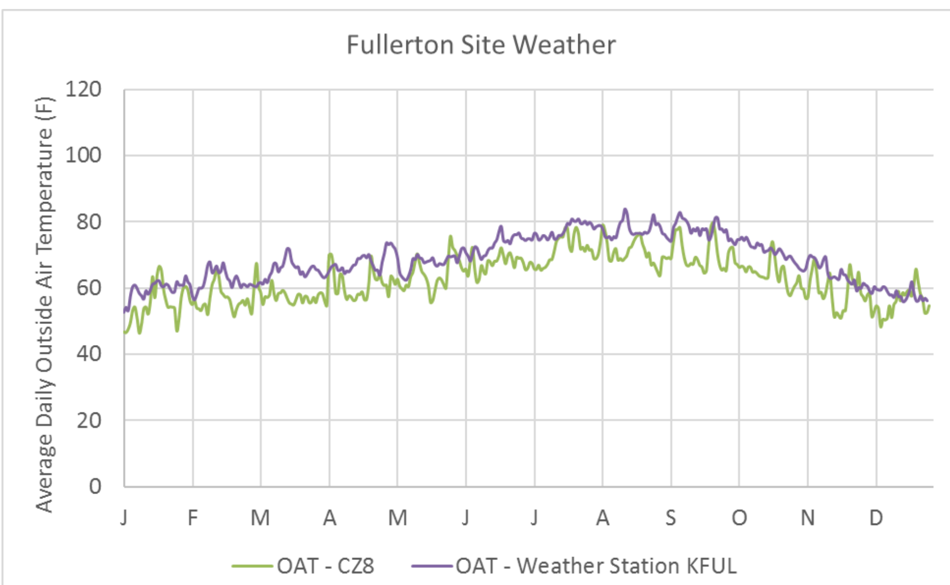

FIGURE 39 - FULLERTON HOST SITE WEATHER AND CZ8

Figure 40 shows the average daily weather used for the normalized annualization the Murrieta host site energy usage.

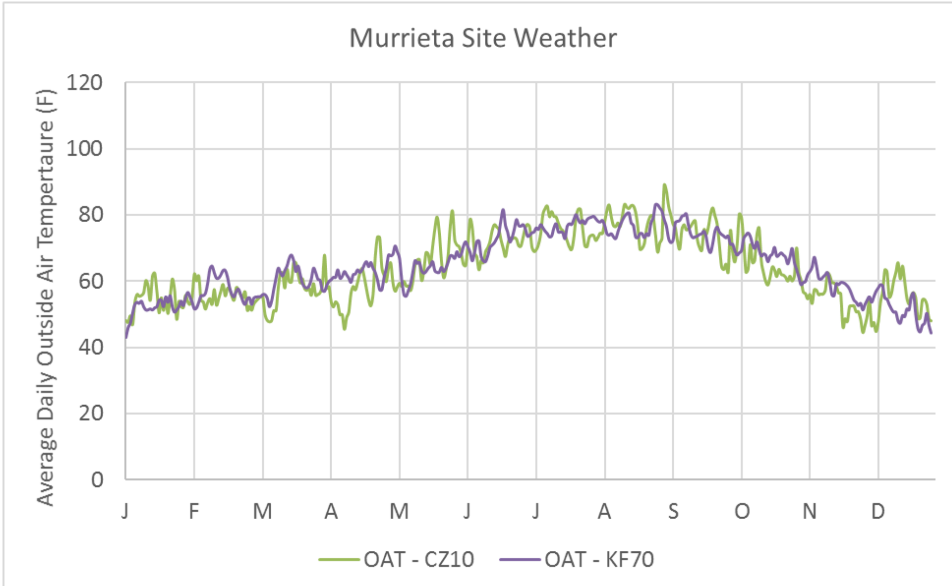

FIGURE 40 - MURRIETA HOST SITE WEATHER AND CZ10

Figure 41 shows the average daily weather used for the normalized annualization the Pomona host site energy usage.

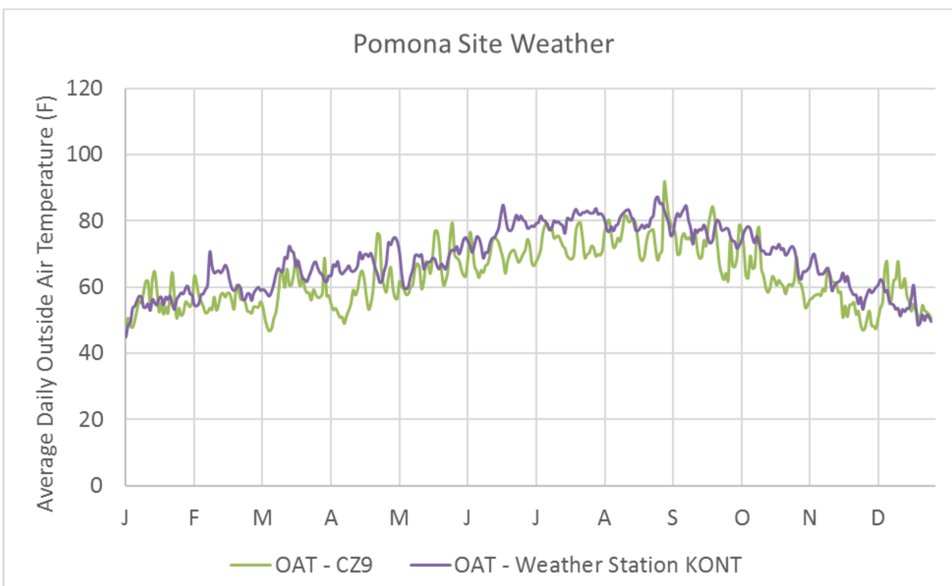

FIGURE 41 - POMONA HOST SITE WEATHER AND CZ9

APPENDIX B – MURRIETA REGRESSION ANALYSIS

Although the authors came to the conclusion that the Murrieta site saw no energy effect, the regression analysis is included here. Regressions consistently showed an unavoidable, unexplained constant shift upwards in the post period, even in comfortable weather conditions.

For the Murrieta site, electrical energy use was found to have a significant relationship to OAT, OAT^2, and IAT. The quadratic term is a result of the nonlinear relationship between heat pump efficiency (and perhaps occupant preferences) to outside air temperature seen in Figure 32. Other regressions options were tested (piecewise, linear, etc.) but all showed similar results. However, note that the post-measure regression is basically shifted up from the baseline by about 2 kWh per day and the relationship to outside air temperature appears to be largely unchanged.

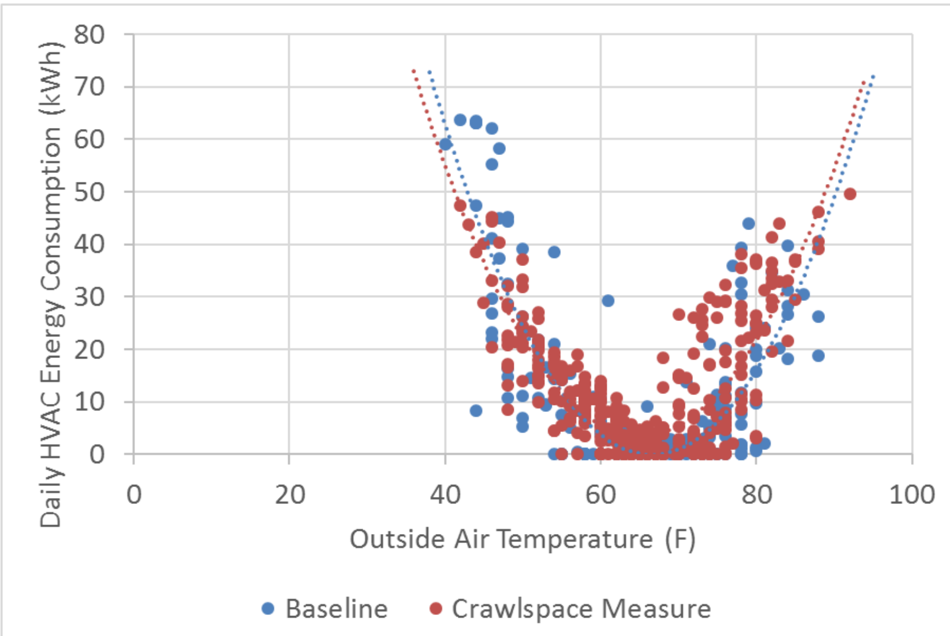

FIGURE 42 – MURRIETA HVAC ENERGY RELATIONSHIP TO OAT

In fact, the difference in normalized energy between the baseline and post-measure conditions were calculated to be just about 750 kWh in CZ10. Thus, based on this uncertainty in normalized savings and stark similarity between the baseline and post-measure case regressions, there was little evidence that the measure significantly affected energy consumption.

Linear regression models for electrical energy usage were established in the following form:

$$Daily\ kWh = A + B * OAT + C * OAT^2 + D * IAT$$

TABLE 30 – MURRIETA ELECTRICAL ENERGY REGRESSIONS

	Baseline	Crawl space Measure
A	288.815	330.923
B	-10.689	-10.932
B t-stat	-15.46	-22.08
B p-value	<0.0001	<0.0001
C	0.074	0.081
C t-stat	12.26	21.33
C p-value	<0.0001	<0.0001
D	1.299	0.538
D t-stat	4.60	3.00
D p-value	<0.0001	0.003
R^2	0.69	0.66

Additionally, since energy consumption had a significant dependence on indoor temperature patterns, normalization of IAT was needed to compare across the measurement periods. When defined as IAT=f(OAT) from the baseline period, comfort conditions during the post period can be modeled as the same as the baseline. Figure 13 shows that IAT can be modeled as

$$IAT = 215 - 7.417 * OAT + 0.115 * OAT^2 - 0.0005 * OAT^3$$

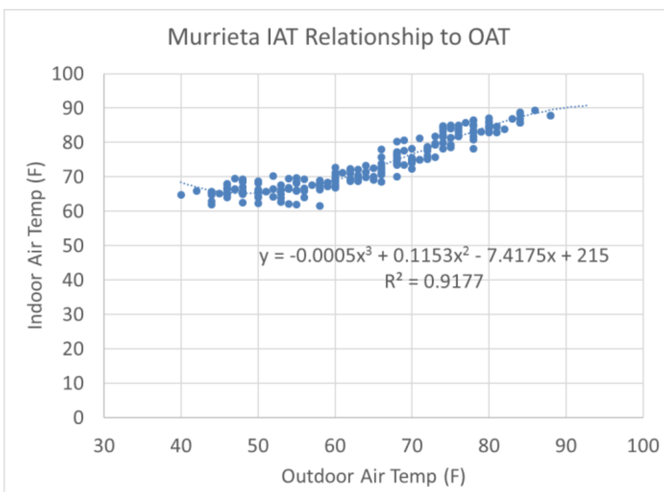

FIGURE 43 - MURRIETA INDOOR TEMPERATURE AS A FUNCTION OF OAT DURING BASELINE

Using these models, the annual energy usage for average host site weather year can be calculated. Since it was observed that the average local weather station daily temperatures differed from California climate zone temperatures, energy usage for the host sites was modeled for an average weather year based on the local weather station over the most recent three years. Figure 44 shows the baseline and crawl space measure annual energy use profiles using the average local weather data.

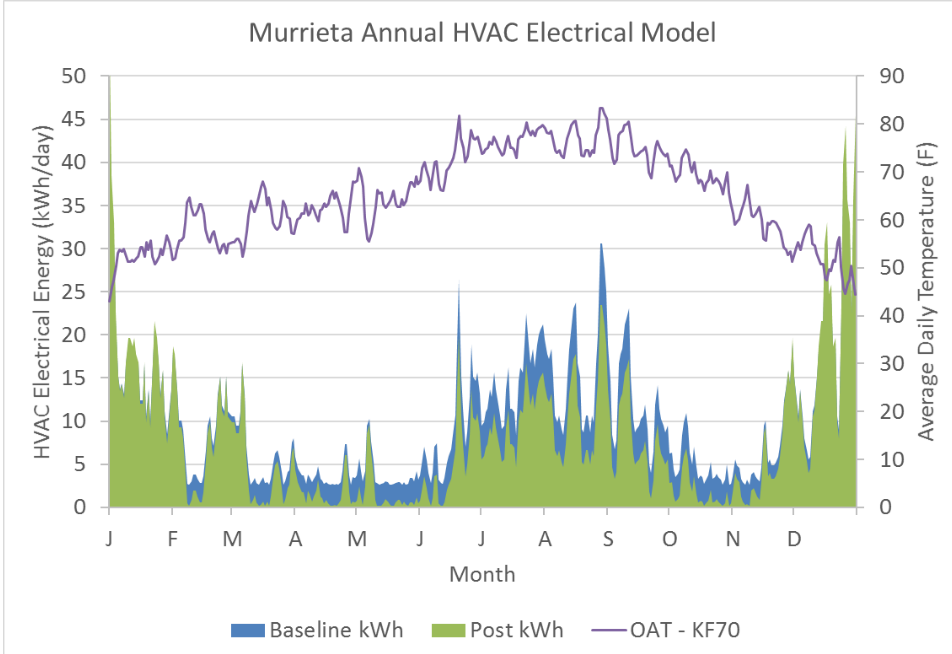

FIGURE 44 – MURRIETA ANNUAL ELECTRIC USE PROFILE

Similar calculations using CZ data can be performed to extrapolate the building type to standard California weather years. Table 31 lists the estimated energy usage and savings for each SCE climate zone and the local weather data for the models established for the Murrieta building type and its occupant behaviors.

TABLE 31 - ENERGY USAGE AND SAVINGS FOR MURRIETA BUILDING TYPE IN SCE CLIMATE ZONES

	BASELINE ELECTRICITY USAGE (KWH/YR)	ELECTRICITY SAVINGS (KWH/YR)
Average Local Weather Station	2,880	-849
CZ8	2,024	-714
CZ9	2,083	-782
CZ10	3,363	-745
CZ15	8,516	-2,578

In all cases, the all-electric model for the Murrieta site showed energy increases for all tested climate zones. Every modeling method tested showed similar increases in energy usage. It is not clear why this is the case, especially since blower door testing showed a decrease in building leakage. However, the Murrieta site data was confounded by a few factors:

- Pre-existing crawl space vapor barrier during baseline period
- Measurement data gap during the baseline summer months
- Changing occupant behavior patterns appear to have resulted in a shift upwards in energy consumption during the post-measure period
- Best-fit regressions were shifted up by a small daily constant in the post-period resulting in increased energy usage roughly equal to this small discrepancy