Design & Engineering Services

Residential Crawl Space Conditioning and Sealing Retrofits

ET14SCE1100 & DR14.07.00 Final Report

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January 2018

Acknowledgements

Southern California Edison's (SCE) Emerging Products (EP) group is responsible for this project. It was developed as part of SCE's Emerging Technologies Program under internal project numbers ET14SCE1100 & DR14.07.00. Ron Kliewer, an EPM project manager at SCE, conducted this technology evaluation with overall guidance and management from Jay Madden and Bach Tsan. Contact Ron.Kliewer@sce.com for more information on this project. SCE and the project staff would like to thank the homeowners and home occupants for their willingness to accommodate the testing, and for their contributions to Energy Efficiency (EE) research.

Disclaimer

EXECUTIVE SUMMARY

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

The study evaluated the sealing and conditioning in existing baseline, vented crawl spaces at single-family residences. Sealed, conditioned crawl spaces have vapor barriers on their earthen floors, insulation on their crawl space walls, and pathways enabling conditioned air to circulate. The sealing measure may improve building envelope air tightness, reduce duct leakage loads, reduce humidity levels, and improve overall air quality. It may also improve Demand Response (DR) effectiveness by increasing available cool air and thermal mass during DR events. Past studies have indicated 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 was observed in the in the hottest Climate Zone (CZ), 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% was observed, while gas usage showed mixed results. Electrical savings were well distributed across summer days, and DR tests showed reductions similar to those of 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 (either energy neutral, or increased regardless of the 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 crawl-space humidity levels, which often lead to mold and rot, were virtually eliminated. The average measure cost was $8.7 per square foot, but this cost may be reduced through standardization and increased market adoption. The existing market size is approximately 1,387,700 and 441,600 homes in California and SCE territory, respectively. If these homes have central air, the estimated potential savings is approximately 400 and 1,100 GWh/year for SCE and California, respectively, assuming the Fullerton and Desert Hot Springs sites are typical.

For further measure support, we recommend a comprehensive modeling and sensitivity analysis similar to those conducted for codes and standards initiatives. This would enable the measure to be studied further, under the control of influential variables and building types. However, common building modeling software cannot replicate conditioned crawl spaces, so 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 their crawl spaces, to achieve the best cost effectiveness and reach the most appropriate group of 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
AFUE	Annual Fuel Utilization Efficiency
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
CT	Current Transducer
CZ	Climate Zone
DR	Demand Response
EE	Energy Efficiency
EUI	Energy Use Intensity
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
O.C.	On Center
pCi/L	Picocurie per Liter
PCT	Programmable Communicating Thermostat
ppm	Parts per Million
SCE	Southern California Edison
SFR	Single-Family Residence
TDV	Time-Dependent Valuation

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INTRODUCTION

Residential Heating, Ventilation, and Air Conditioning (HVAC) energy usage is affected by many variables. These include occupant comfort preferences and behavior, primary equipment specifications and maintenance, building characteristics, and weather. Building characteristics include parameters such as thermal resistance, air leakage, duct design, and other construction features. In general, as houses age and building characteristics degrade, energy consumption tends to increase. For instance, without corrective action, building leakage typically gets worse over time, and HVAC energy usage 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.

Some houses have crawl spaces, typically below or on grade under their floors. They are basically shallow, unfinished basements which provide space for piping, ducting, conduit, floor supports, underfloor insulation, and other building components. Crawl space design is critical, because it can impact the energy needed for heating and air conditioning (AC).

Crawl spaces can be categorized as conditioned or unconditioned, and vented or unvented. Unconditioned crawl spaces have no air transfer between HVAC systems and living spaces, and usually have vents leading to the outside, which are meant to allow for passive ventilation. Unconditioned crawl spaces sometimes have insulation under living space floors, between the crawl spaces and living spaces. In some cases, unconditioned crawl spaces may have vapor barriers installed on their earthen floors, to reduce thermal transfer to the soil, moisture transfer from the soil, and radon gas influx.

FIGURE 1 – UNCONDITIONED, VENTED CRAWL SPACE EXAMPLE

Conditioned crawl spaces have no venting to the outside. Instead, they have insulated exterior walls and passive or forced air circulation with HVAC systems or living spaces. These crawl spaces usually have vapor barriers installed, often required by code.

High humidity conditions and condensation may appear in crawl spaces, especially when hot, humid daytime temperatures swing dramatically to cooler conditions at night. Moisture also transfers from bare soil floors into crawl spaces. Excessive crawl space moisture can cause issues such as dry rot, mold, termites, swelling, buckling, and poor Indoor Air Quality (IAQ). It is normally recommended that Relative Humidity (RH) levels stay below 70%, to avoid the condensation and moisture buildup that can cause these problems (EPA, 1991).

In the past, it was believed that venting crawl spaces was an effective, affordable way to manage moisture. Early building codes required crawl spaces to be vented, under the assumption that natural, wind-driven ventilation would help reduce humidity and remove standing or condensed water. However, 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 do not necessarily cost less, 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).

There are also 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 US residential buildings found that building air tightness and envelope leakage was worst in homes with vented crawl spaces, especially older homes and those with ductwork in the crawl space (Chan, Joh, & Sherman, 2012).

In summary, issues that may arise from vented, unconditioned crawl spaces include:

- Increased living space air leakage, exfiltration, and infiltration through the floor.
- Increased loads from leaky ducts in crawl spaces.
- High moisture, dry rot, and mold potential in crawl spaces, driven by moisture in earth and condensation.
- Stack effect (pulling cold air from crawl spaces into living spaces during the 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 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 homes prior to any intervention, as detailed in the Technical Approach section. These baseline conditions are similar to the large, existing building stock that has 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 US 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).

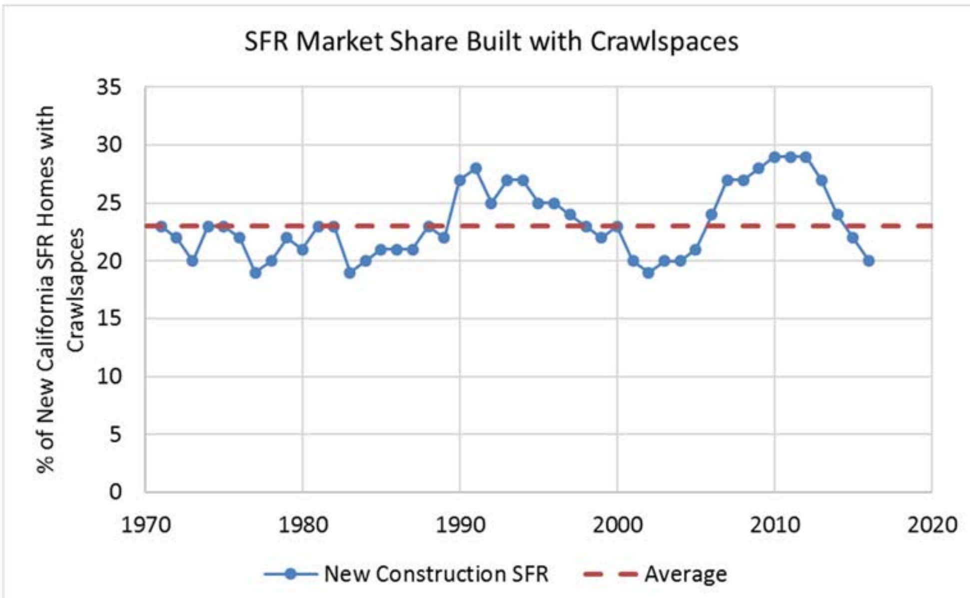

FIGURE 2 - CALIFORNIA SFR MARKET SHARE BUILT WITH CRAWL SPACES (US CENSUS BUREAU, 2017)

Potential existing market size can be estimated based on a variety of market survey data sources. We can use this estimate to characterize the total available EE resources, as well as the target market size for retrofit, training, or code measure programs.

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 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 US, 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

As stated above, homes with vented crawl spaces tend to have the highest leakage rates, especially if ductwork is located in the crawl spaces (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 have ductwork in their crawl spaces, but roughly 66% of SFR buildings with crawl spaces in SCE territory, and 56% statewide, have central air.

Crawl space design has a significant effect on building air tightness, so it is important to understand the average California SFR leakage rate. It is reported at 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 CZs should have leakage rates at or below three ACH50 (International Code Council), meaning average existing California homes are about five times leakier than this code guideline. Some of this excessive air leakage travels through crawl space pathways.

[1] As of available 2015 data.

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 progress toward improving unvented crawl space market adoption. However, adoption rates in new construction remain low, and crawl space sealing retrofits in existing homes are negligible (Lstiburek, 2004).

This study was designed to gather data and draw conclusions on unvented, conditioned crawl spaces, to provide useful information for market transformation. It evaluates the potential impacts of the measure in retrofit scenarios, using field study results from 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 existing building stock's potential. While costs and experimental controls may be better in new construction, the 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).

Over the past 20 years, several studies have quantified the moisture management and energy benefits of unvented, conditioned crawl spaces. One early study in a heating-intensive CZ 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, 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 showed varying results. A 2009 study found mixed savings of about 15% at new construction test sites in Louisiana, but neutral energy effects in Flagstaff (Dastur, Mauceri, & Hannas, 2009). However, the study confirmed sealing would keep humidity within safe bounds, regardless of climate zone or season. A study published in 2007 found little energy benefit to conditioning and sealing crawl spaces in a new construction test home in the Pacific Northwest (Building Industry Research Alliance, 2007). However, the study also covered other measures, used an insulated floor baseline, and may not have included air circulating 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 during the heating season, but an energy benefit in the summer cooling months (Biswas, Christian, & Gehl, 2011). However, results suggested conditioned, sealed crawl spaces had little overall energy benefit compared to vented crawl spaces with underfloor insulation.

The primary difference between past referenced studies and this one is 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 (either to each other, or to this one). Instead, together they form a more comprehensive understanding of conditioned crawl spaces under different conditions.

The studied retrofit measure comprises a vapor barrier that covers the entire crawl space ground and wall area. Furthermore, since existing crawl space wall and vent geometries are often irregular and interface with the outside, rigid spray foam sealing and insulation may 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, to complete 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 may be modified with returns, or air supplies in the crawl space plus vents in the floor can allow air to 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 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 are located in the crawl space.

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

- Vent and entry sealing, with a vapor barrier on the walls and ground.
- Spray foam insulation on the exterior crawl space walls.
- Forced conditioning via return ducts (or a fan, in ductless homes) and registers transferred to the living space.
- Programmable Communicating Thermostats (PCTs) 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. The Murrieta site's baseline included a crawl space with 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 toward further study, and decide which statewide and utility programs are most aligned with the measure's potential. For instance, the measure may overlap with EE and DR programs, codes and standards, building modeling software development, and others. The findings may help determine which of these programs and their stakeholders should be involved in future efforts, market transformation, or support roles.

To that end, this study has several objectives:

1. Measure the 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, EE and DR 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, over two years, a field assessment was conducted at four existing residential sites. The first year was for baseline monitoring, and the second year was for measure monitoring. The Technical Approach section of this document provides details on collected data, project timelines, host site conditions, and other measurement and analysis plan specifics.

TECHNICAL APPROACH

Since the research covered the measure's retrofit applications, it was studied in a field assessment at four existing SFR buildings across SCE territory. Table 5 outlines some primary site characteristics. The sites had higher energy-use intensities than the average California home, and except for the Pomona site, had average building air leakage. The host sites were selected based on their appropriateness for the retrofit measures, how well they represented typical existing residential building stock, and the willingness of participants to engage in comprehensive testing. Since the test was invasive and extensive, participant willingness was a primary site recruitment challenge. Due to the small sample size, the field assessment was meant to be a case study more than an analysis representative of market-wide potential or impacts (such as a 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 (1^{st} floor) 940 (2^{nd} floor)	4.33	n/a
Pomona	9	1920	37.6	1,160	7.36	n/a

This is a brief overview of the host sites:

All four sites were typical of wood-framed houses in the years they were built. The exterior walls were framed with 2x4 studs, 16" on center (O.C.). The attics were also wood framed, with dimensional lumber rafters (no engineered trusses). The main difference was the Pomona house, which was vintage 1920 and framed with rough-sawn dimensional lumber, not smooth-planed lumber as the other three homes were. This had no effect on the research outcome – it is just a description of the site conditions.

The four homes' building envelope differences are the insulation, doors, and windows. Details are listed in Table 6 – Building Envelope Baseline Specifics.

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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 – Building Envelope Baseline Specifics

Host Site	Year Built	Construction	Roof	Exterior Doors	Windows	Window Shading	Wall	Attic
Desert Hot Springs	1946	Wood frame: 2 x 4 wall studs, conventional rafter framing	Asphalt shingle	Solid wood	Single pane, wood frame, untinted	Blinds on all windows, closed during the day	R11 fiberglass batt	Loose fill FG over R11 FG batts, R33 overall
Fullerton	1957	Wood frame: 2 x 4 wall studs, conventional rafter framing	Asphalt shingle	Solid wood and dual pane glass patio slider	Double pane, vinyl frame, untinted	Blinds on most windows, open during the day	None	R38 loose fill cellulose
Murrieta	1980	Wood frame: 2 x 4 wall studs, conventional rafter framing	Asphalt shingle	Front door solid wood, back door wood with medium window	Mix of single and double pane, wood frame, untinted	No shading	R11 fiberglass batt	R19 FG batts between joists, with some significant gaps
Pomona	1920	Wood frame: 2 x 4 wall studs, conventional rafter framing	Asphalt shingle	Front door solid wood, back door wood with medium window	Single pane, wood frame, one vinyl kitchen window	Curtains on most windows, closed during the day	None	Small amount of loose fill and R19 FG batts; many uncovered joists and open spaces

Table 7 outlines the baseline conditions and measure specifics unique to each test site.

TABLE 7 – 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; floor registers installed in three corners of house to foster airflow between living space and crawl space

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

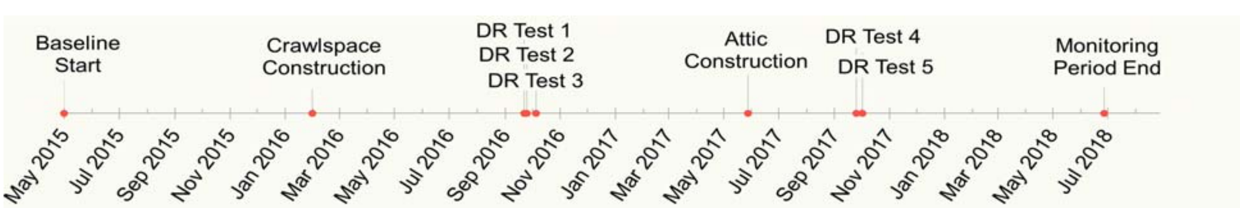

FIGURE 4 – PROJECT TIMELINE

Per International Performance Monitoring and Verification Protocol (IPMVP) guidelines, instrumentation and data collection points were selected, to help get a complete view of the buildings' responses to the technology. Measurement points followed 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 necessary to establish normalized energy savings for the systems affected by the measures. Gas usage and savings was determined with Option C by using gas billing data instead of an independent sub-system measurement. Additionally, we collected several other data points, to confirm the measures did not negatively affect IAQ and building health metrics.

The measurement points and instrumentation are listed in Table 8. Additional details on instrumentation and data points for each site are listed in the subsequent site description sections.

TABLE 8 – DATA COLLECTION POINTS AND INSTRUMENTATION OVERVIEW

MEASUREMENT	INSTRUMENTS	LOGGING INTERVAL
Power monitoring (fans, condensers, compressors, package units, window units)	Current Transducers (CTs) with amperage data loggers, spot measurements of power factor and voltage	One minute
Natural gas usage	Southern California Gas utility metering	Billing period
Temperature and RH – indoor, outdoor, attic, and crawl space	Onset HOBO® sensors and data loggers	15 minutes
Heat Degree Day (HDD) and Cooling Degree Day (CDD)	Local airport weather station	One hour
Soil temperature	Onset HOBO sensors and data loggers	15 minutes
Carbon monoxide (CO) – indoor, outdoor, attic, and crawl space	Dwyer CO data logger	Five minutes
Indoor radon	Family Safety Products Safety Siren	Short- and long-term averages

Although data was logged at intervals of one, five, and 15 minutes, the data was eventually consolidated to hourly and daily intervals. Analysis began at short intervals, but the buildings' response times and the regression analysis required longer intervals to establish usable regression equations. At all sites, data was stored in onsite loggers, and manually retrieved about every three months. While resulted 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 set points, occupied hours, HVAC scheduling, building maintenance, personal preferences, and other such variables were beyond experimental control. For tighter control of all relevant experimental variables and true measure isolation, unoccupied building or lab testing would be required, under controlled conditions.

Data was used to establish energy usage relationships to independent weather variables. By establishing normalized energy usage relative to weather, we were able to compare controlled energy usage before and after measure implementation. Non-weather variables (such as weekday, season, and time of day) were explored for normalization, but only weather and Indoor Air Temperature (IAT) were found to be significant variables.

To calculate normalized energy savings, we calculated linear regression equations for each building's electrical and natural gas energy. In general, these relationships were calculated as follows:

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

Where *E* is daily electrical or natural gas energy, *OAT* is the outdoor air temperature, and *IAT* is the indoor air temperature. Not all variables were needed for each site. Many types of regressions, with differing independent variables, were tested for viability. They were 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 (OATs) were averaged across three years of local weather station data so an annual, localized weather pattern could be used in addition to CA CZ weather data. This is because the host site local weather differed 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 two-year-old, 13 SEER, three-ton packaged unit with an 80% Annual Fuel Utilization Efficiency (AFUE) gas furnace rated at 60 MBtu/hr. The two residents 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 set point thermostat. The attic had 13 inches of R11 blown insulation, and the single pane windows were not tinted.

Table 9 shows the home's measurement points. Although each site was slightly different, the same type of data was monitored at each site and for each phase (baseline and measure case).

TABLE 9 - DESERT HOT SPRINGS MEASUREMENTS

MEASUREMENT	UNIT	LOGGING INTERVAL	EQUIPMENT
Package unit current	Amps	One minute	Onset HOBO data logger and CT
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

Measurement	Unit	Logging Interval	Equipment
Outside, inside, attic, and crawl space air RH	%	15 minutes	Onset HOBO data loggers and sensors
OAT and degree days	°F and DD	Sub-hourly	Local weather station data service
OARH	%	Sub-hourly	Local weather station data service
Natural gas usage (whole building)	therm	Billing period	SoCalGas utility-grade meter
Crawl space six-inch subsurface soil temperature	°F	One minute	Onset HOBO data logger and sensor
Crawl space 18-inch subsurface soil temperature	°F	One minute	Onset HOBO data logger and sensor
Outside, inside, attic, and crawl space CO	ppm	Five 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 three-ton split system, 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 set point 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, prior to a hole leading into the crawl space being added during the measure construction.

The home's measurement points are shown in Table 10.

Table 10 - Fullerton Measurements

Measurement	Unit	Logging Interval	Equipment
Outdoor condenser/compressor unit current	Amps	One 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	One 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

MEASUREMENT	UNIT	LOGGING INTERVAL	EQUIPMENT
Outside, inside, attic, and crawl space air RH	%	15 minutes	Onset HOBO data loggers and sensors
OAT and degree days	°F and DD	Sub-hourly	Local weather station data service
OARH	%	Sub-hourly	Local weather station data service
Natural gas usage (whole building)	therm	Billing period	SoCalGas utility-grade meter
Crawl space six-inch subsurface soil temperature	°F	One minute	Onset HOBO data logger and sensor
Crawl space 18-inch subsurface soil temperature	°F	One minute	Onset HOBO data logger and sensor
Outside, inside, attic, and crawl space CO	ppm	Five 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, two-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 home had a whole-house fan with 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 upper-floor window units were used occasionally in the summer. The attic had about eight inches of bat insulation, with moderate coverage.

The home's measurement points are shown in Table 1.

TABLE 11 - MURRIETA MEASUREMENTS

MEASUREMENT	UNIT	LOGGING INTERVAL	EQUIPMENT
Packaged unit current	Amps	One 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	One 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 RH	%	15 minutes	Onset HOBO data loggers and sensors
OAT and degree days	°F and DD	Sub-hourly	Local weather station data service
OARH	%	Sub-hourly	Local weather station data service
Crawl space six-inch subsurface soil temperature	°F	One minute	Onset HOBO data logger and sensor
Crawl space 18-inch subsurface soil temperature	°F	One minute	Onset HOBO data logger and sensor
Outside, inside, attic, and crawl space CO	ppm	Five 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 2.

Table 12- Pomona Measurements

Measurement	Unit	Logging Interval	Equipment
Window unit power	kW	One minute	Onset HOBO UX18-120 plug load logger
Transfer fan current	Amp	One 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 RH	%	15 minutes	Onset HOBO data loggers and sensors
OAT and degree days	°F and DD	Sub-hourly	Local weather station data service
OARH	%	Sub-hourly	Local weather station data service
Crawl space six-inch subsurface soil temperature	°F	One minute	Onset HOBO data logger and sensor
Crawl space 18-inch subsurface soil temperature	°F	One minute	Onset HOBO data logger and sensor
Outside, inside, attic, and crawl space CO	ppm	Five minutes	Lascar CO EL-USB-CO300 data logger
Inside radon levels	PCi/L	Running average	Safety Siren Series 3 radon meter

RESULTS

Baseline and post-measure energy use was compared for each site, to ascertain the measures' energy savings potential. 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 spaces. IAT and RH stayed closer to the typical comfort range over the observed range of outside air conditions. Additionally, radon and CO levels were not adversely affected, and tended to stay within safe ranges in both the baseline and post-measure cases. Humidity in the crawl spaces 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 133 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 the measure had little effect on energy use, as discussed in the following sections and Appendix B.

TABLE 13 - 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 hHeat – 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.

California CZ weather data was used to calculate HVAC energy usage and savings for each site. Table 144 lists the estimated savings for each building, in their respective CZs. These extrapolations to the various zones are all based on one example for each type of building, and should be considered a set of case studies rather than a statistically-significant dataset. The results are covered in the Discussion and Conclusions section of this document.

TABLE 14 – 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 CO levels in the living spaces. CO 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. Various agencies have several recommended exposure limit standards, but there is no statewide code, other than a requirement for new single-family residences to 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 lower than 5 ppm in the Southwest Region of the US, which 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. The data logger had a rated accuracy of ±5 ppm, designated by the dashed line above the measured averages.

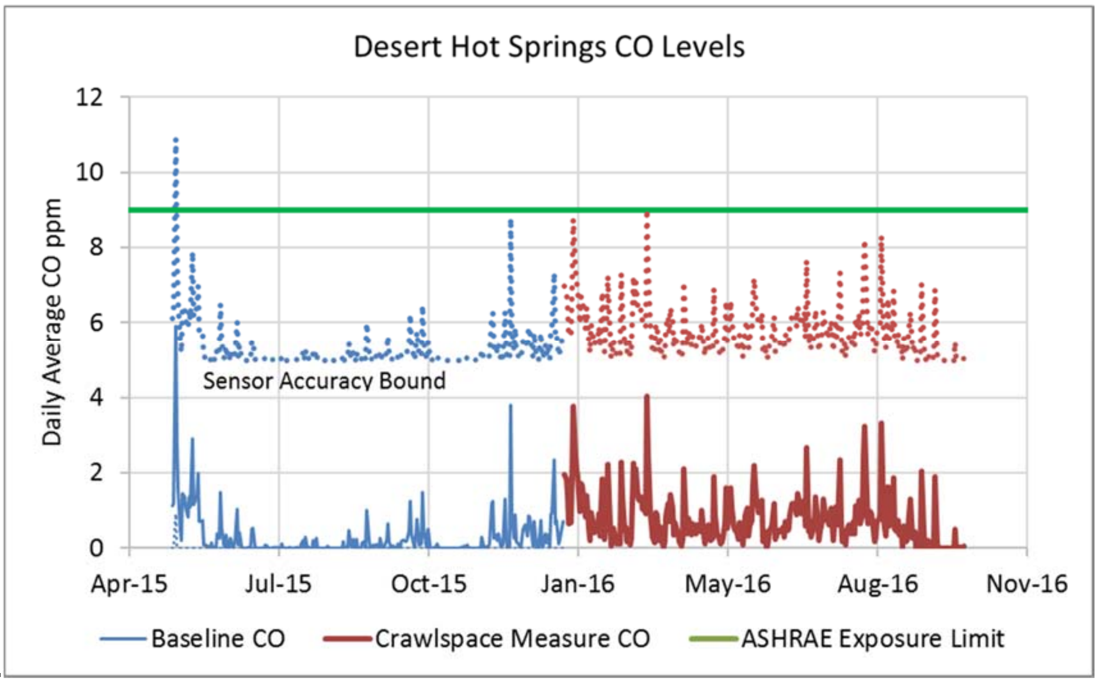

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FIGURE 5 - DESERT HOT SPRINGS CARBON MONOXIDE MONITORING

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 the measure did not negatively affect or increase CO concentrations to unsafe levels inside the living spaces.

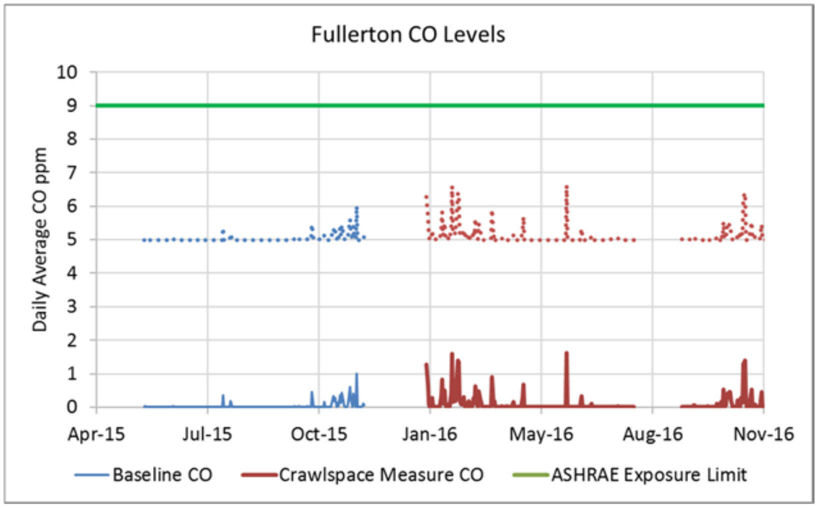

FIGURE 6 - FULLERTON CARBON MONOXIDE MONITORING

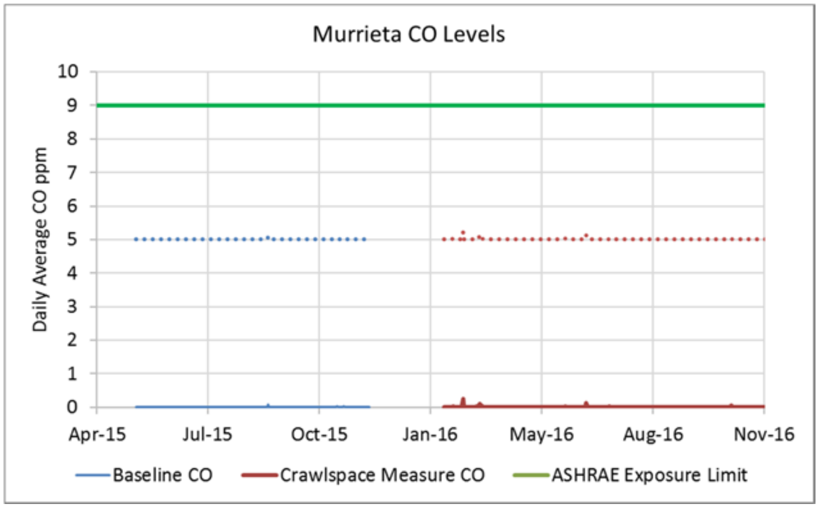

FIGURE 7 - MURRIETA CARBON MONOXIDE MONITORING

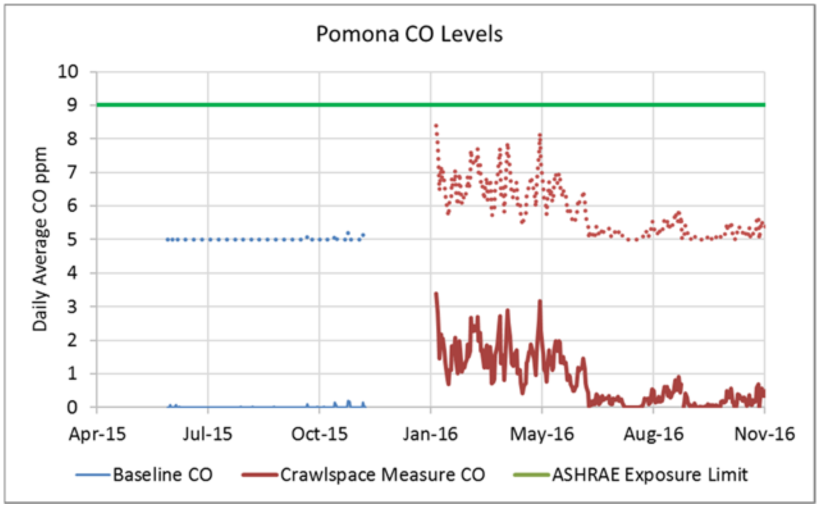

FIGURE 8 - POMONA CARBON MONOXIDE MONITORING

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

In Figure 9, the reduced slope from the baseline to the post-measure case shows the crawl space air humidity was less dependent on outside air conditions, meaning less air infiltration generally resulted in lower humidity. This is reflected in 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 RH range. Sealing the crawl spaces resulted in 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 above 70% in Pomona. The Fullerton, Murrieta, and Pomona sites went from having 1-4% of time spent above 70% crawl space RH to 0%. Thus, the measure is an obvious benefit in terms of moisture reduction and mold prevention, and will keep humidity below recommended limits.

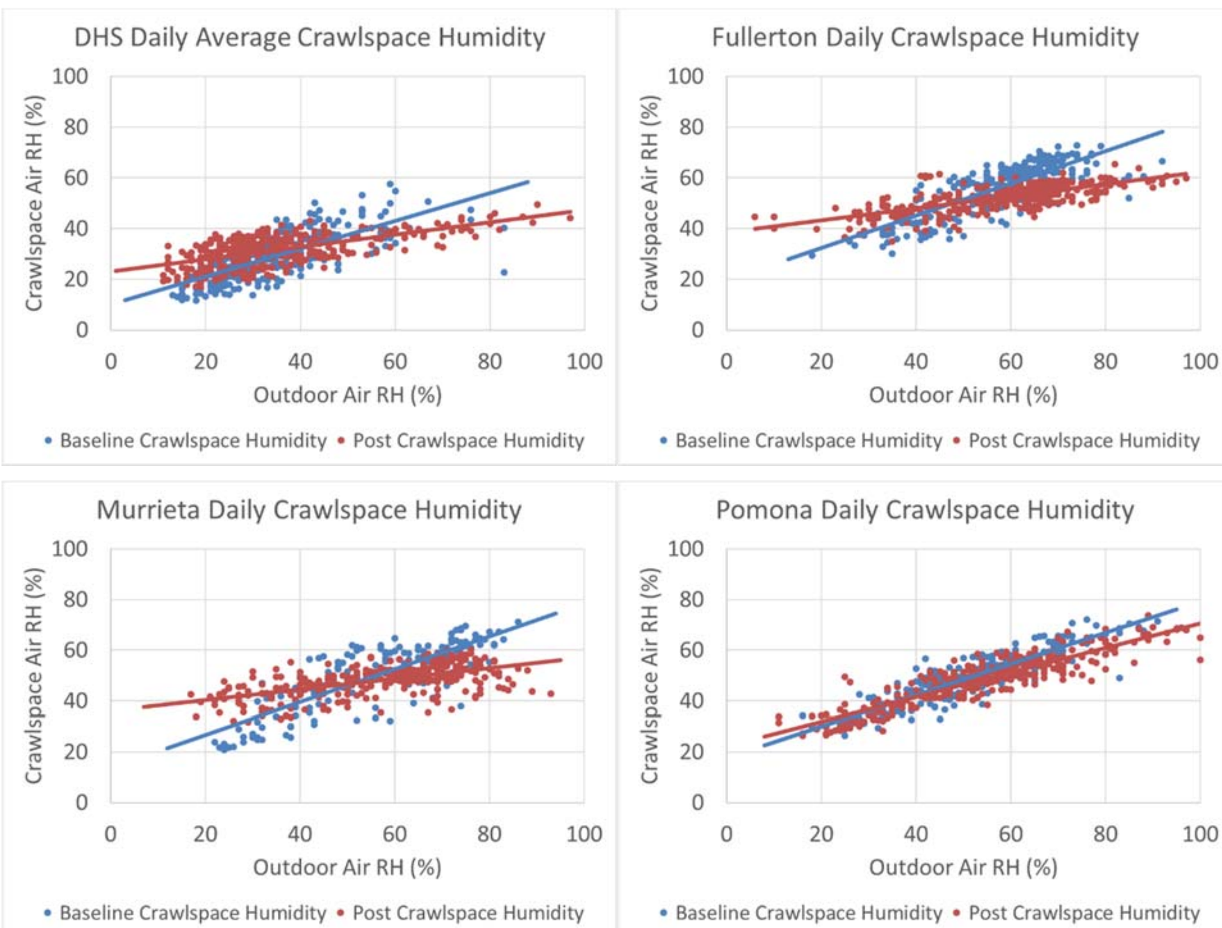

FIGURE 9 – CRAWL SPACE AIR HUMIDITY RELATIONSHIP TO OUTSIDE AIR HUMIDITY

Another important indoor health metric is home radon levels. Radon, measured in pCi/L, can enter houses when released from foundation soil and rocks. Mitigating high levels of radon often involves forced crawl space ventilation. Thus, it is conceivable that sealing crawl spaces could affect the levels of radon entering and accumulating in the home. However, vapor barriers can also prevent radon from entering. Although there is no standard for safe home radon levels, mitigation is typically recommended if levels are above 4 pCi/L (Environmental Protection Agency, 2012). Household alarms typically sound when levels exceed that value.

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

TABLE 15 – 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 was a 1946 single-story building in CZ15. It had 900 square feet of living space, a three-ton package unit with gas heat, ductwork in the crawl space, and no shade. Blower door testing indicated the building had envelope air leakage rates, as shown in Table 6. The crawl space sealing measure reduced air leakage by about 15%, demonstrating conditioned air and loads lost due to outside air transfer was substantially reduced. 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 16 - 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 did not follow the same trend during the baseline and crawl space measure periods. The figure shows IATs were 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 occupant comfort levels. Under perfect experimental controls, IATs would remain consistent; however, occupant behaviors and set points were not under control.

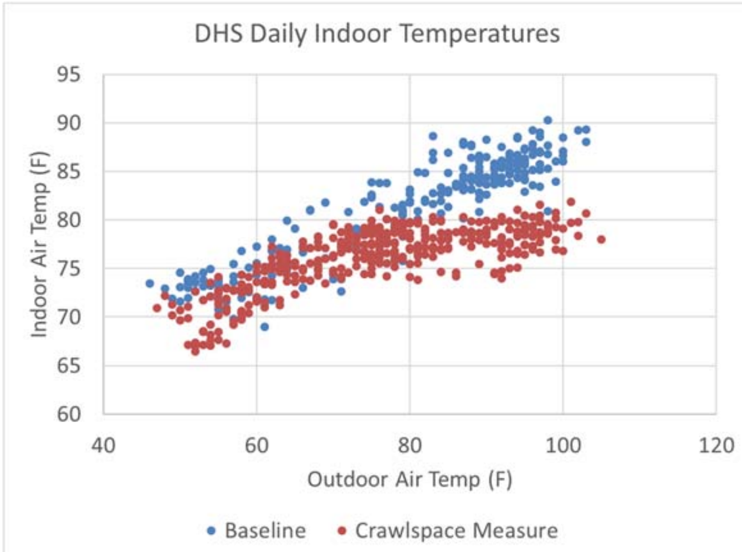

FIGURE 10 - DESERT HOT SPRINGS INDOOR AIR CONDITIONS

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

- Lower average OATs during the crawl space measure period.
- Decreased loads on the cooling system (reduced 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 Figure 11's psychrometric chart of daily average indoor air conditions. The indoor air data cluster contracts significantly, and comfort conditions improve.

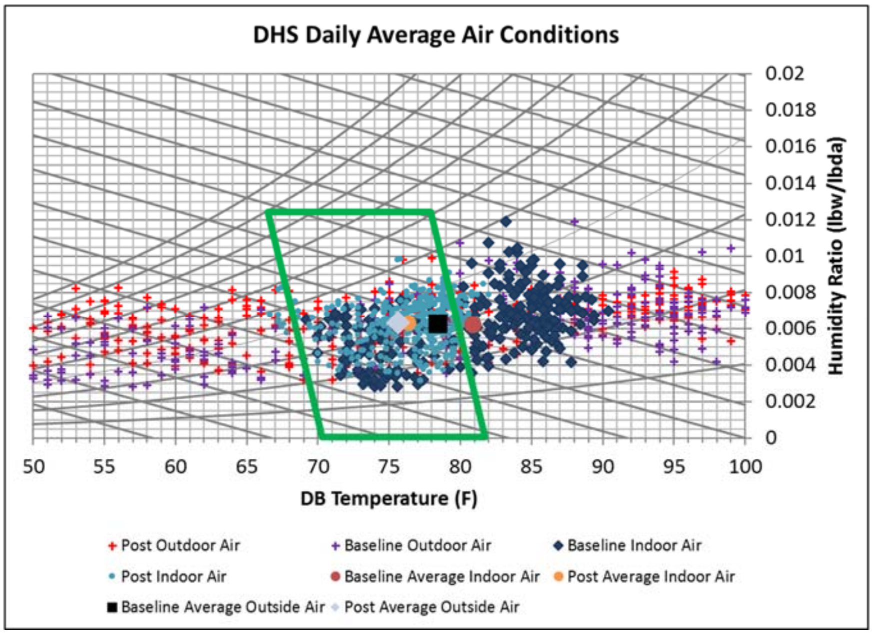

FIGURE 11 – DESERT HOT SPRINGS BASELINE AND CRAWL SPACE MEASURE CASE PSYCHROMETRIC CHART (DAILY AVERAGES)

Normalization of energy use to OATs and IATs may account for 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, OAT, and control settings. This choice of independent variables can account for the change in controls and apparent occupant preferences from the baseline to the post-crawl-space measure period.

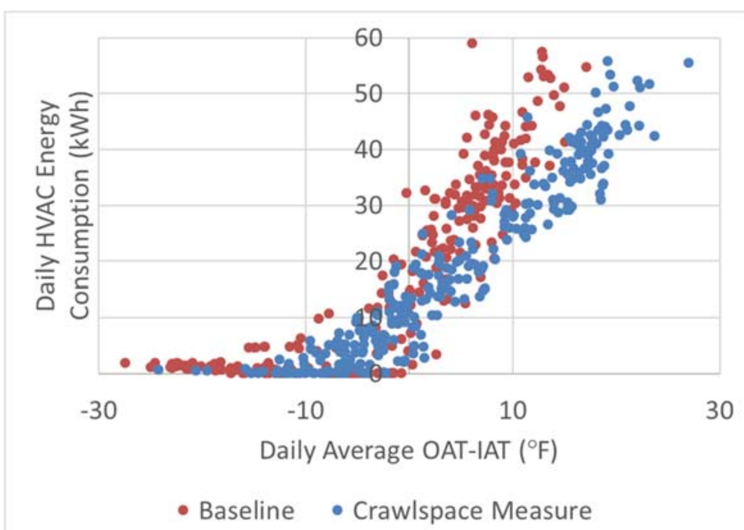

FIGURE 12 – DESERT HOT SPRINGS HVAC ENERGY RELATIONSHIP TO ENVELOPE TEMPERATURE DIFFERENCE

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 177.

TABLE 17 – 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 was implemented, IAT normalization was required. When defined as IAT=f (OAT) from the crawl space measure period, comfort conditions could be modeled as consistent across the baseline and measure periods. The indoor air conditions during the post-measure period were selected because they followed a pattern more typical of standard thermostat set points than the baseline period.

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

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

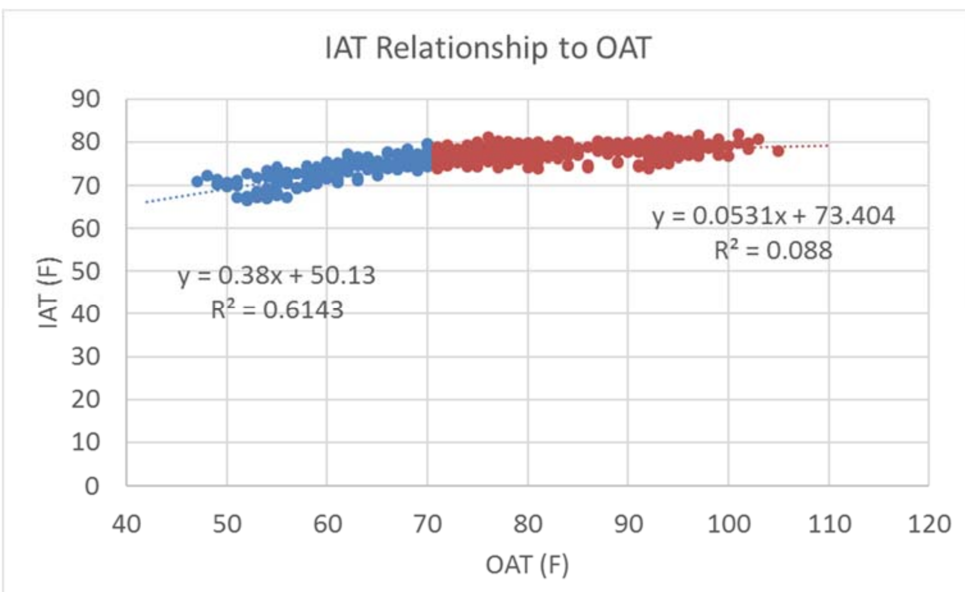

FIGURE 13 - DESERT HOT SPRINGS INDOOR TEMPERATURE AS A FUNCTION OF OAT DURING BASELINE

Similarly, linear regressions for gas consumption may 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 change point of 75°F.

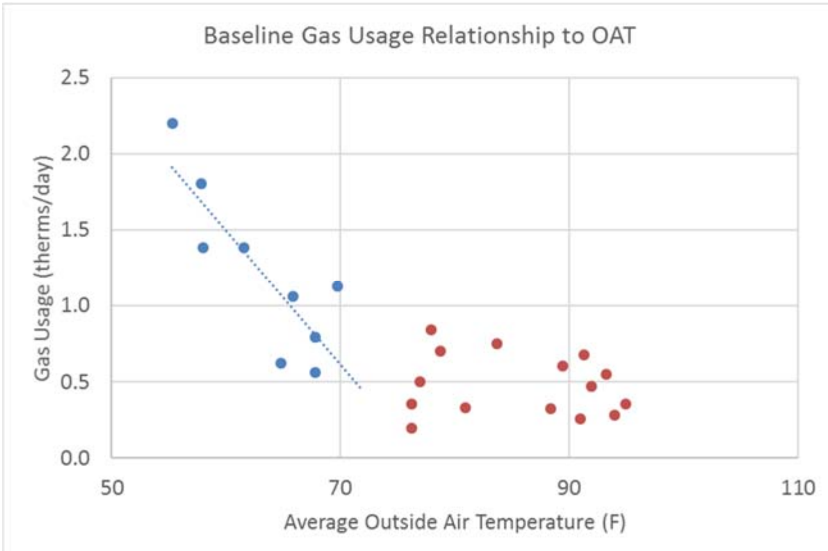

FIGURE 14 – DESERT HOT SPRINGS BASELINE GAS ENERGY USAGE RELATIONSHIP TO OAT

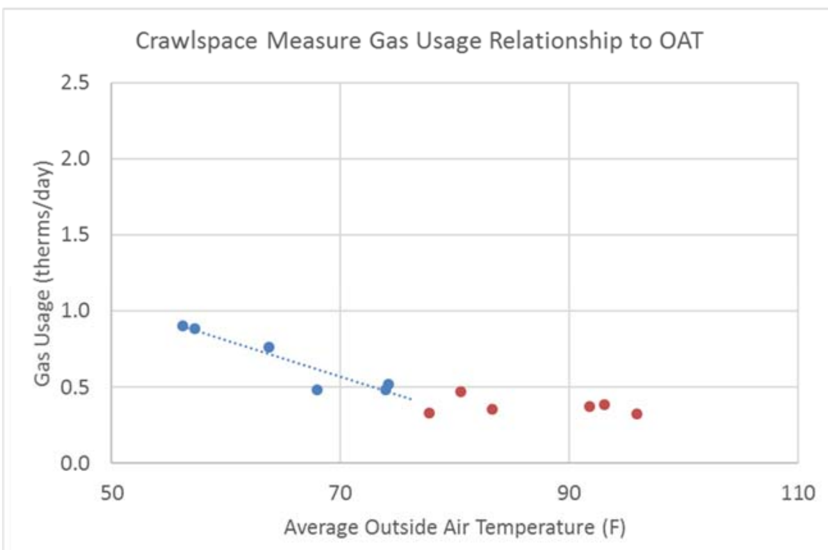

FIGURE 15 – DESERT HOT SPRINGS MEASURE GAS USAGE RELATIONSHIP TO OAT

Weighted linear regressions to average billing period OAT were established as follows:

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

A can be thought of as average daily appliance gas usage, not including space conditioning.

TABLE 18 – 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 adjust 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 follows.

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

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

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

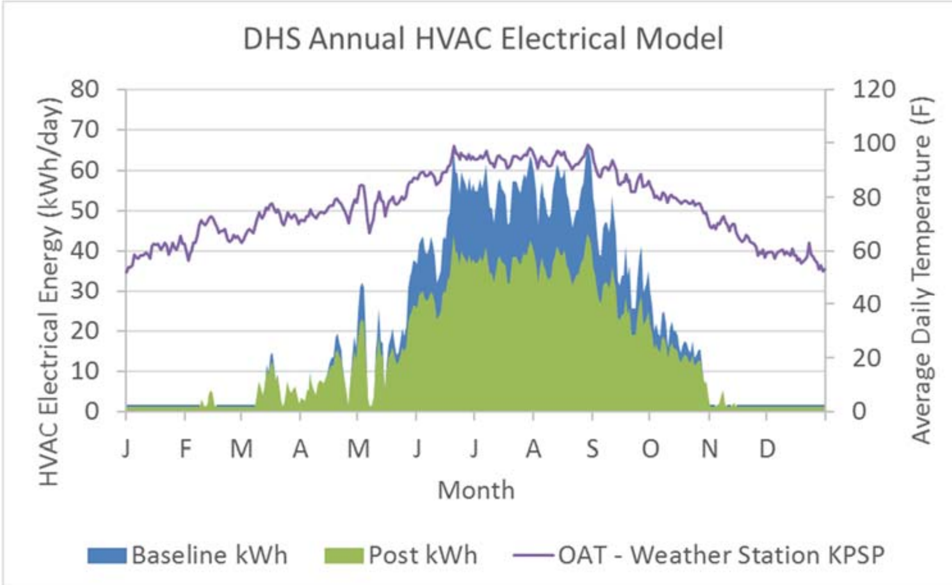

FIGURE 16 – DESERT HOT SPRINGS ANNUAL ELECTRIC USE PROFILE

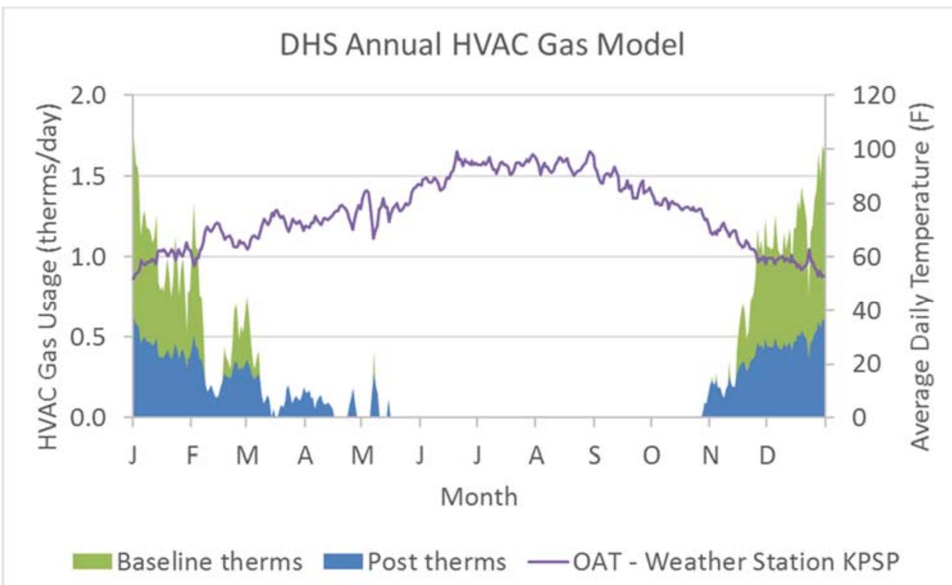

FIGURE 17 - DESERT HOT SPRINGS ANNUAL GAS USAGE PROFILE

Similar calculations using CZ data can be performed to extrapolate the building type to standard California weather years. Table 19 lists the estimated energy usage and savings for each site's CZ, as well as 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 19 – 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

The installed measures also included DR-capable thermostats. Since these were installed during the crawl space retrofits, no baseline DR tests were conducted. However, several DR tests were conducted during the measure phase. This was to characterize DR potential and determine whether the crawl spaces, as well as the attic sealing and conditioning, showed any obvious DR benefits, such as increased demand reduction or thermal inertia, which would help maintain comfortable inside temperatures during DR events.

During DR test event, thermostat cooling set points were increased by 1°F per hour for three hours, starting at 2:00 p.m. Demand curves from an adjusted 10-in-10 baseline and the event day showed obvious demand reduction and increased inside temperatures, as shown in Figure 18 and Figure 19. The IAT sensor was not located at the thermostat, but closer to the ceiling, to remain hidden. Thus, Figure 19 shows inside temperatures increased by several degrees, but this was not necessarily what the occupants felt.

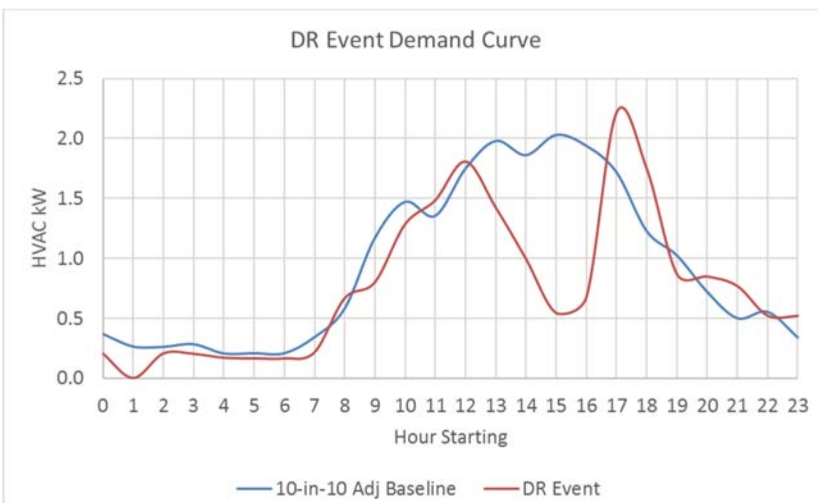

FIGURE 18 – DESERT HOT SPRINGS DR TEST EXAMPLE

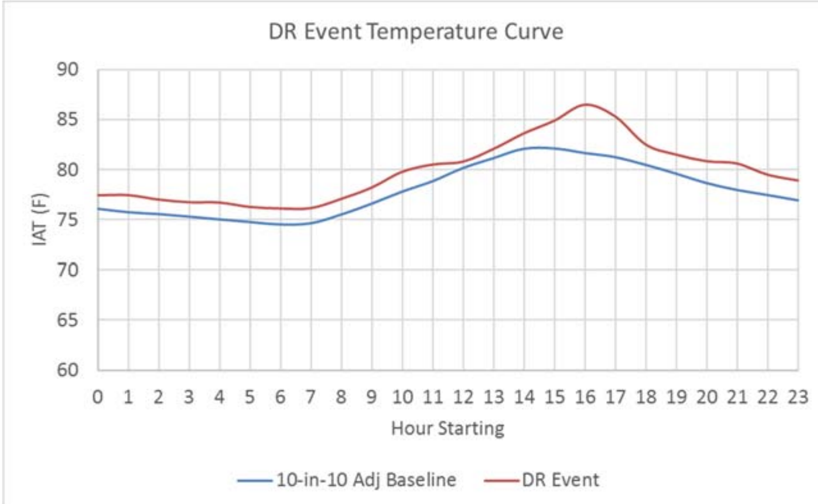

FIGURE 19 – DESERT HOT SPRINGS DR TEST EXAMPLE

Table 20 shows hourly-averaged DR test results from 2:00 p.m. to 5:00 p.m., indicating an average demand reduction of about 1.14 kW during peak time.

TABLE 20– 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 three-ton split system with gas heat, a centrally-located air handler, and attic ductwork. Blower door testing showed the building had envelope air leakage rates as shown in Table 1.

TABLE 21 - 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 either a measurement error, or most of the leakage was through the attic. The 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 had a slightly different relationship to OAT during the baseline and crawl space measure periods, although not as divergent as the Desert Hot Springs site.

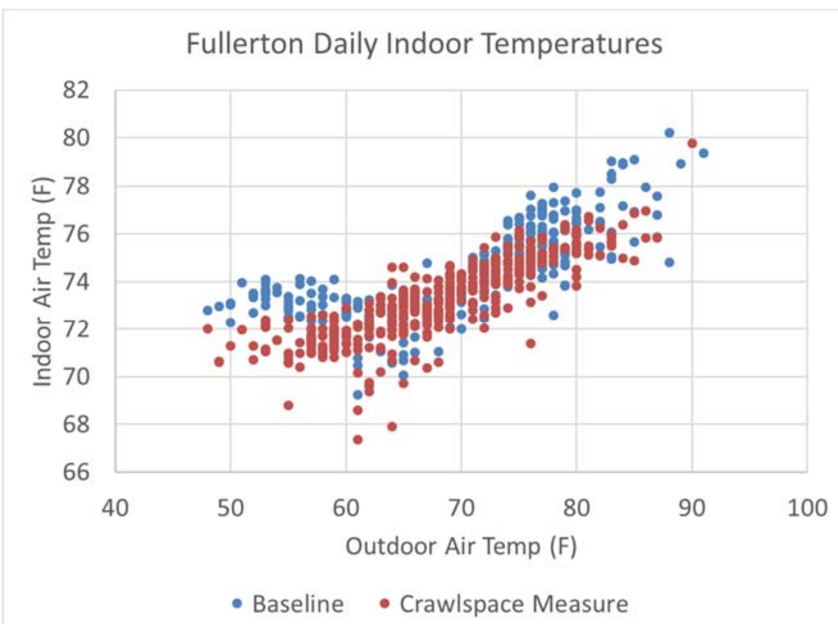

FIGURE 20 – FULLERTON INDOOR AIR TEMPERATURE CONDITIONS

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

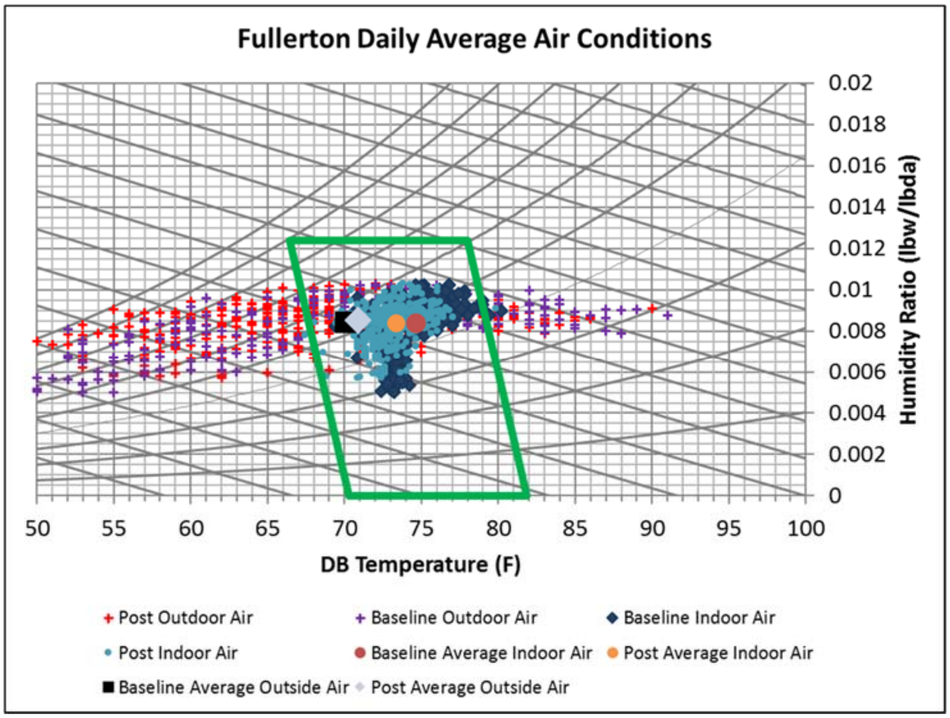

FIGURE 21 – FULLERTON BASELINE AND CRAWL SPACE MEASURE CASE PSYCHROMETRIC CHART (DAILY AVERAGES)

Normalization of energy use to outdoor and IATs 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*.

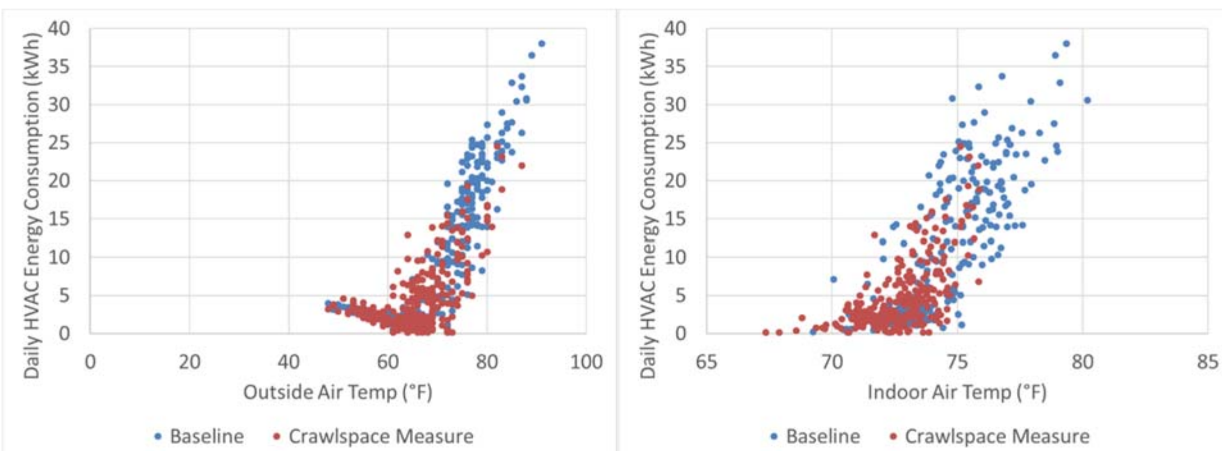

FIGURE 22 – FULLERTON HVAC ENERGY RELATIONSHIP TO OAT AND IAT

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 22 – 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:

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

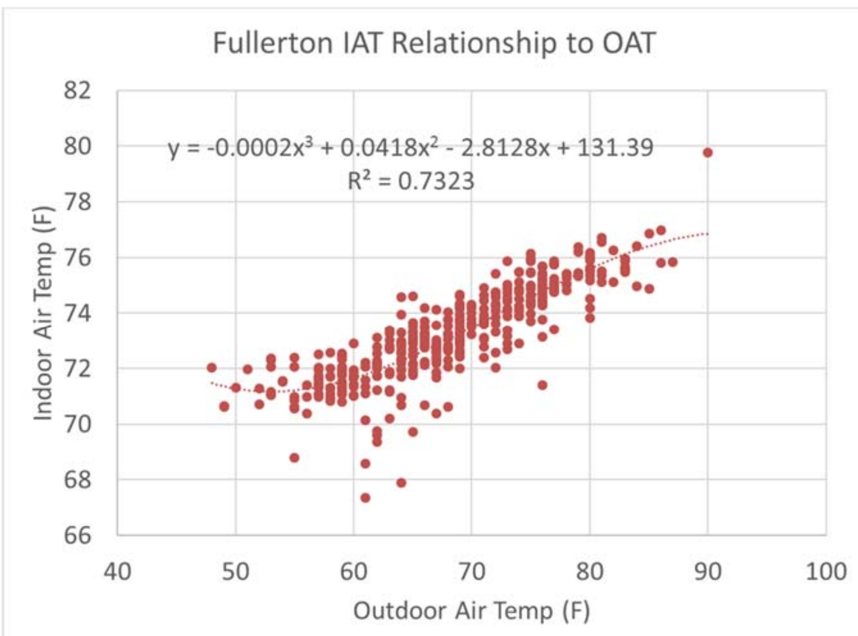

FIGURE 23 - FULLERTON IAT AS A FUNCTION OF OAT DURING CRAWL SPACE MEASURE PERIOD

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 change point around 68°F.

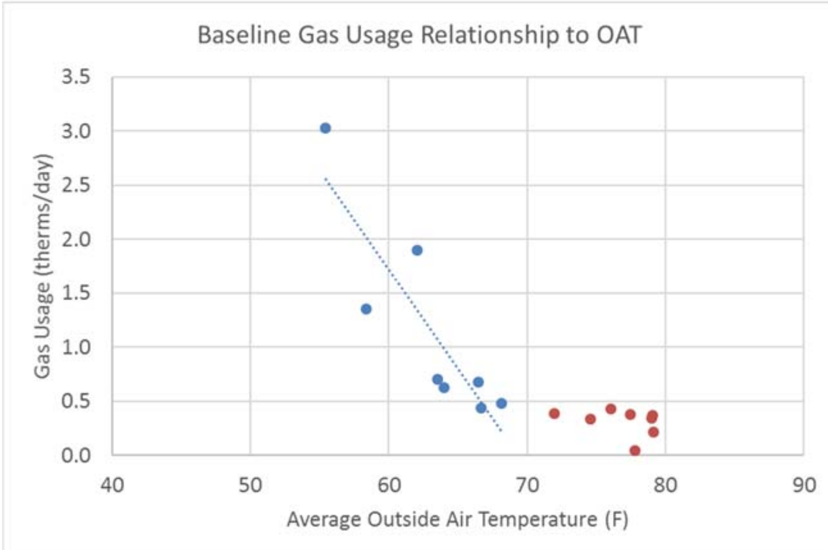

FIGURE 24 – FULLERTON BASELINE GAS USAGE RELATIONSHIP TO OAT

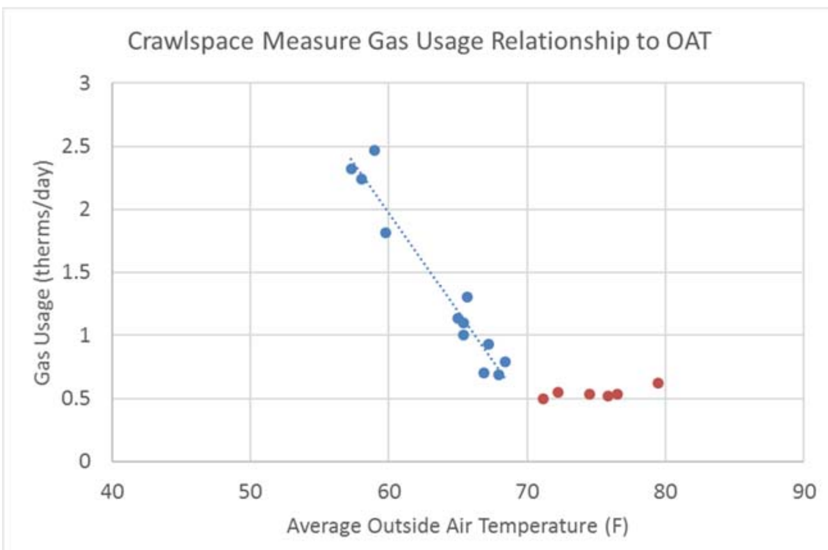

FIGURE 25 – FULLERTON MEASURE GAS USAGE RELATIONSHIP TO OAT

Weighted linear regressions to average billing period OAT were established as follows:

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

TABLE 23 – 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 adjust 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 several-year baseline billing data period.

We can use these models to calculate the annual energy usage for an average host site weather year. Since we observed the average local weather station daily temperatures differed from California CZ temperatures, energy usage for the host sites was modeled for an average weather year based on local weather station temperatures from 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.

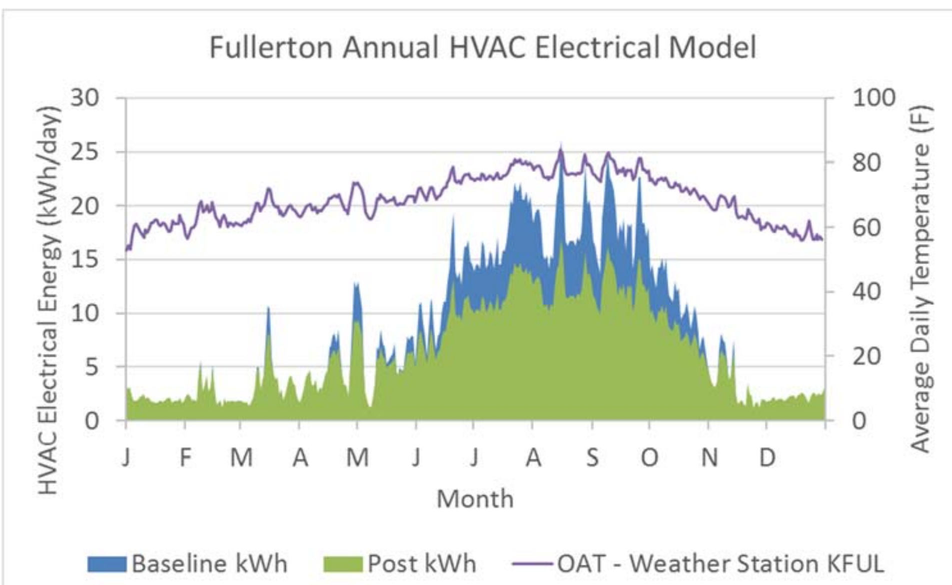

FIGURE 26 – FULLERTON ANNUAL ELECTRIC USE PROFILE

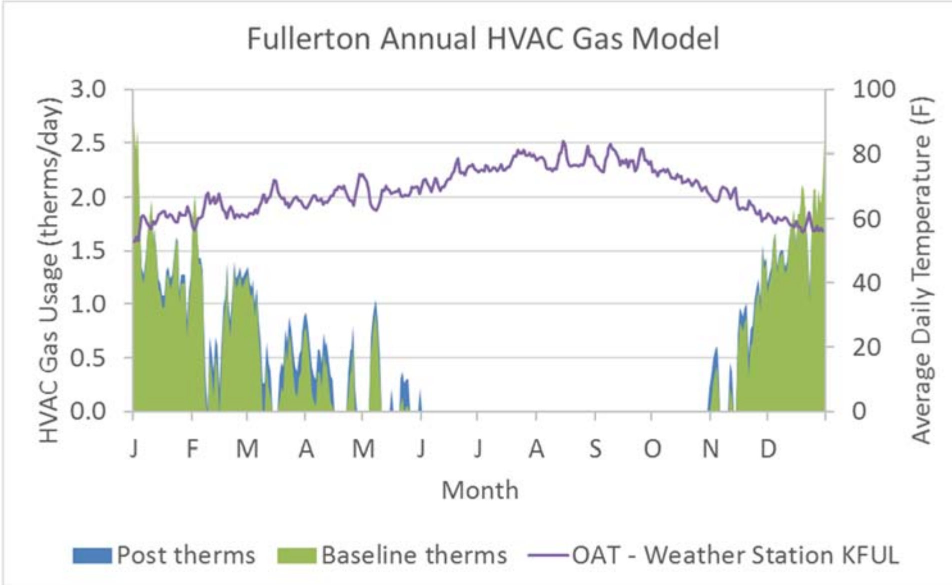

FIGURE 27 - FULLERTON ANNUAL GAS USAGE PROFILE

Similar calculations using CZ data can be performed to extrapolate the building type to standard California weather years. Table 4 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 24 – 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 summer day, especially during daytime hours.

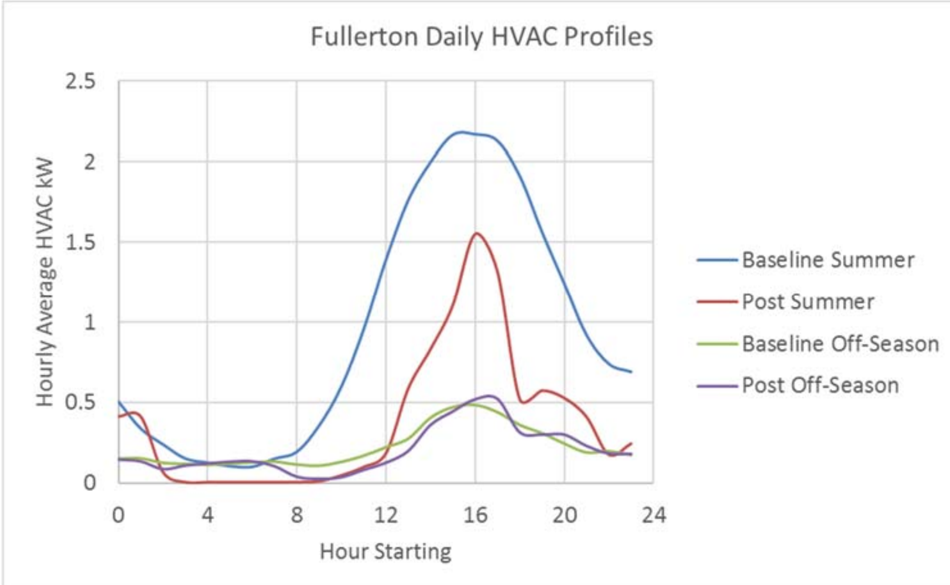

FIGURE 28 – DAILY DEMAND PROFILE FOR FULLERTON SITE

The installed measures included DR-capable thermostats. 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. This was to characterize the DR potential and determine whether the crawl spaces, as well as the attic sealing and conditioning, showed any obvious DR benefits, such as increased demand reduction or thermal inertia, to maintain comfortable inside temperatures during DR events.

For the DR test event, thermostat cooling set points were increased by 1°F per hour for three hours starting at 2:00 p.m. Demand curves from an adjusted 10-in-10 baseline and the event day showed obvious demand reduction and increase in inside temperatures, as shown in Figure 29 and Figure 30. The IAT sensor was not located at the thermostat, but was closer to the ceiling, to remain hidden. Thus, Figure 30 shows inside temperatures increased several degrees, but that was not necessarily what the occupants felt.

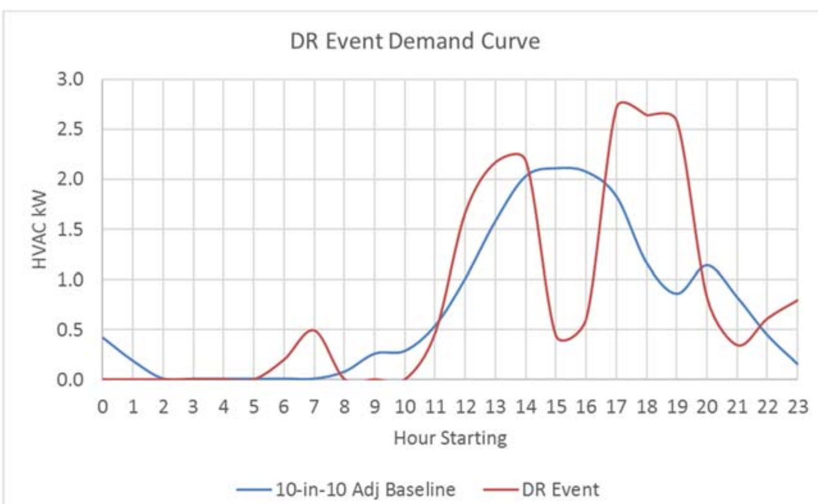

FIGURE 29 – FULLERTON DR TEST EXAMPLE

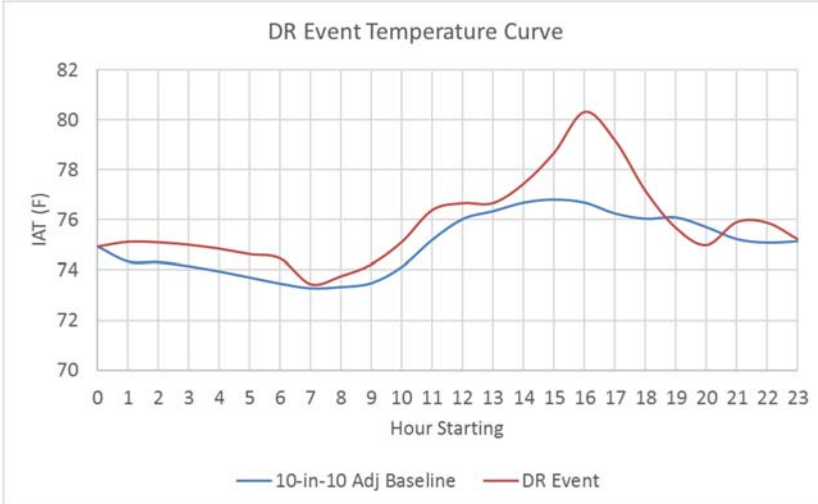

FIGURE 30 – FULLERTON DR TEST EXAMPLE

Table 255 shows the hourly-averaged DR test results for the hours of 2:00 p.m. to 5:00 p.m., indicating an average demand reduction of about 0.95 kW during the peak timeframe.

TABLE 25– 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 on the first floor, and 940 on the 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 on 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, prior to the study.

Blower door testing showed the building had envelope air leakage rates indicated in Table 266. The crawl space sealing measure improved building air tightness by about 8%.

TABLE 26 - 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.

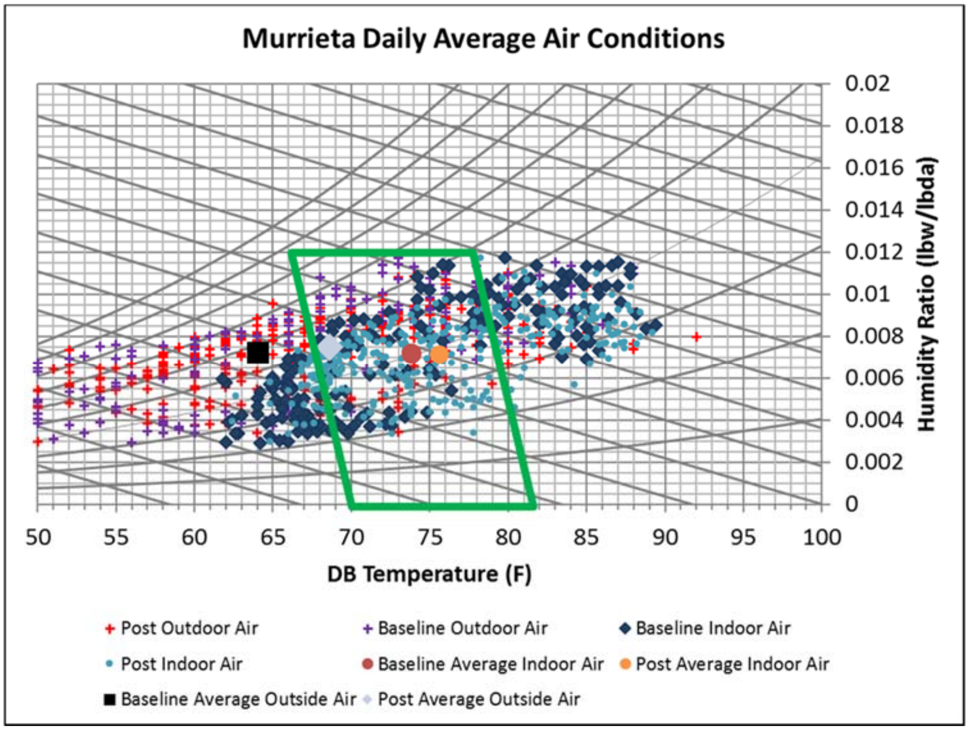

FIGURE 31 – MURRIETA BASELINE AND CRAWL SPACE MEASURE CASE PSYCHROMETRIC CHART (DAILY AVERAGES)

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 OAT, as shown in Figure 32. Other regression options were tested (piecewise, linear, etc.) but all showed similar results. However, the post-measure regression basically shifted up from the baseline by about two kWh per day, and the relationship to OATs appears to be largely unchanged.

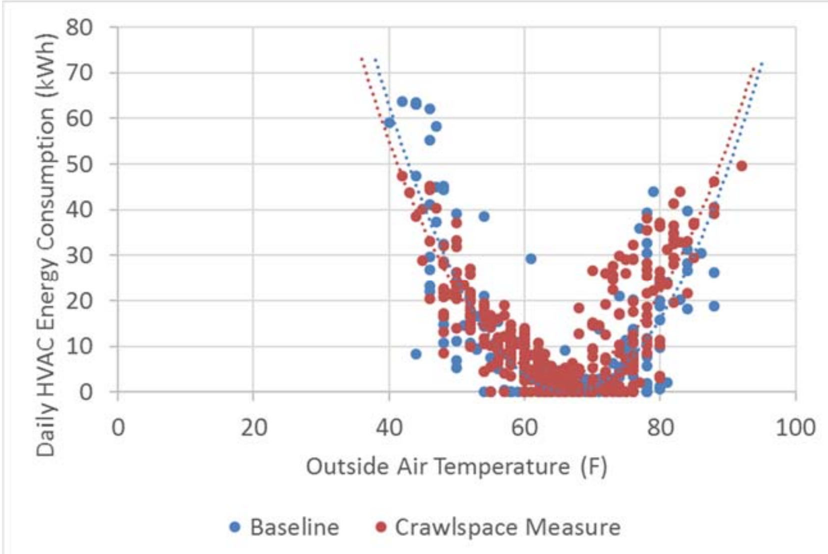

FIGURE 32 – MURRIETA HVAC ENERGY RELATIONSHIP TO OAT

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

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

WINDOW UNITS – POMONA

The Pomona site is a 1920 single-story building in CZ9, with 1,160-square feet of living space and two window units. Blower door testing showed the building had envelope air leakage rates indicated in Table 277. 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 27 - 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 IAT normalization was necessary in the Pomona energy modeling, as it was for the other sites.

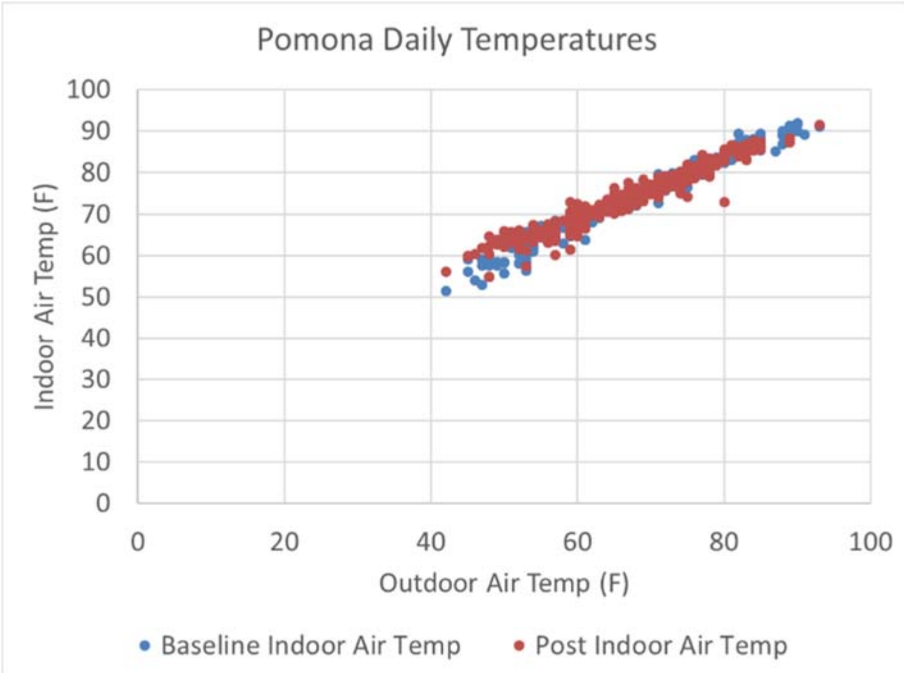

FIGURE 33 - POMONA INDOOR AIR CONDITIONS

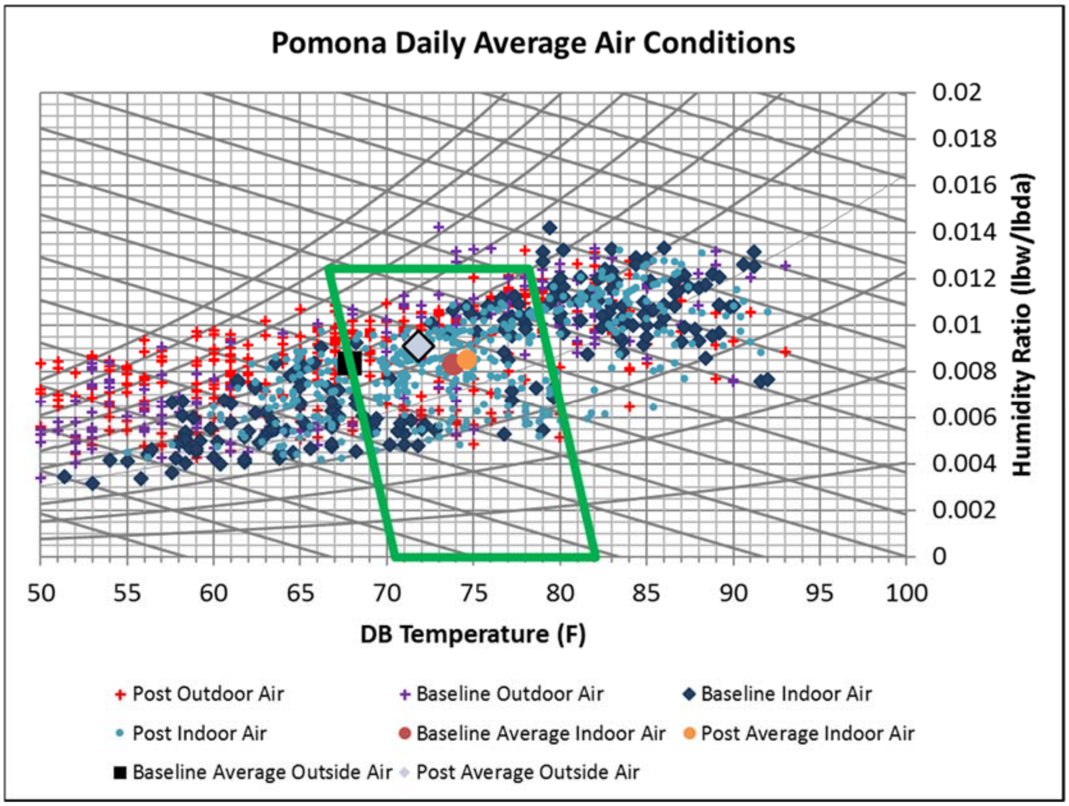

FIGURE 34 – POMONA BASELINE AND CRAWL SPACE MEASURE CASE PSYCHROMETRIC CHART (DAILY AVERAGES)

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

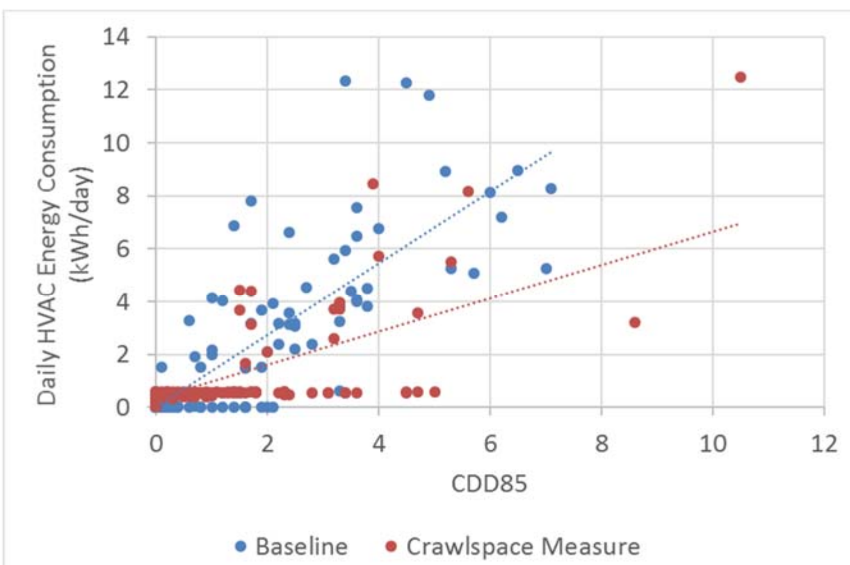

FIGURE 35 – POMONA HVAC ENERGY RELATIONSHIP TO CDD85

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 areas. 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 28 – 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 average local weather data.

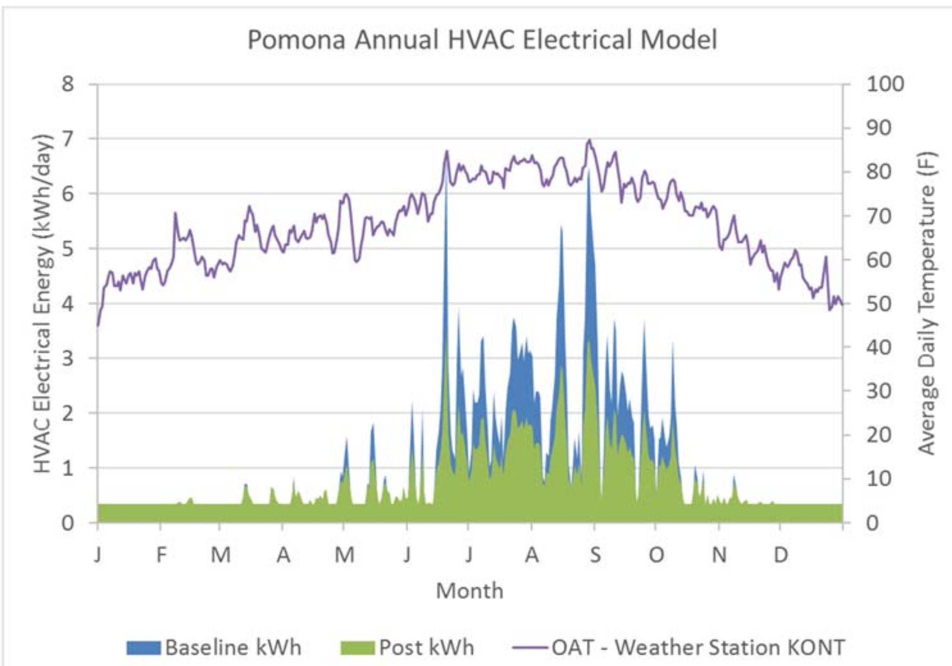

FIGURE 36 – POMONA ANNUAL ELECTRIC USE PROFILE

Similar calculations using CZ data can be performed to extrapolate the building type to standard California weather years. Table 1929 lists the estimated energy usage and savings for each SCE CZ, and the local weather data for the models established for the Pomona building type and its occupants' behaviors.

TABLE 629 – 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 optimally set. 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 the 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.

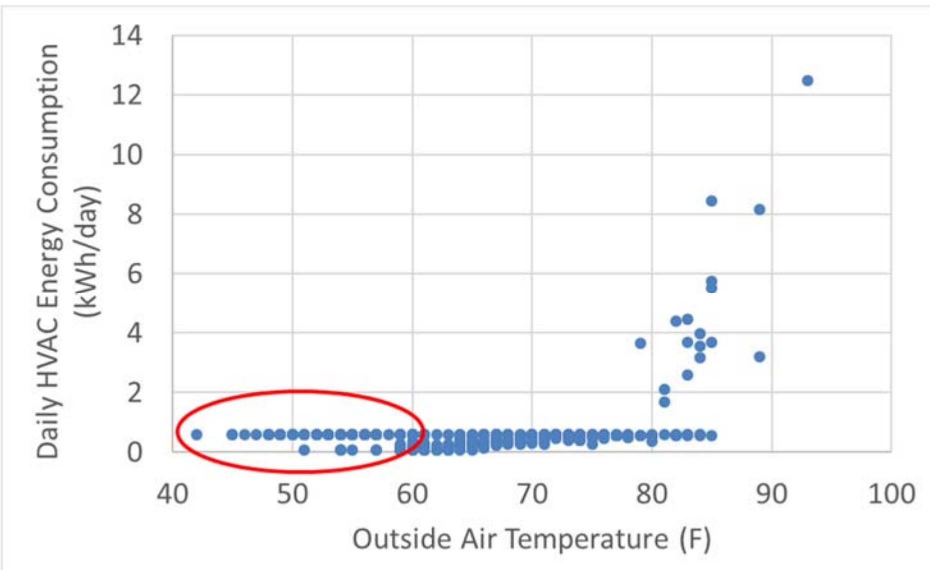

FIGURE 37 – POMONA CRAWL SPACE MEASURE PERIOD DAILY KWH OVER OAT SHOWING SUBOPTIMAL TRANSFER FAN OPERATION

By that reasoning, the fan should have been turned off when the 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 3030. Generally, energy usage and savings are low, because the occupants had an unusually-large comfort zone, and the cooling equipment was rarely used.

TABLE 30 – 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 capability, since the window units could not be controlled by a PCT or other DR-enabled control.

DISCUSSION AND CONCLUSIONS

This field assessment of conditioned, sealed crawl spaces 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 CZs for comparison. Indoor air quality was observed, and DR tests were performed during the measure period. Market size, potential savings, and barriers were studied. The measure is particularly useful for homes with ductwork in their crawl spaces, high envelope leakage, high duct leakage, excessive crawl space venting, and high HVAC energy usage. Baseline conditions without vapor barriers already installed would experience more savings.

Two sites provided optimal 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 others. They showed annual HVAC electric savings of about 21 and 28%, and whole-building electric Energy Use Intensity (EUI) savings of 10% and 18%. These numbers 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 expected, 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 CZ, and with ducting in the crawl space.

The other two sites had some confusing test conditions, and may not have been entirely representative of typical buildings or situations that should be targeted for this measure. The Murrieta site showed inconclusive results, which may suggest the baseline and measure used about the same amount of energy. This site was confounded by a baseline with a vapor barrier already installed, as well as unusual occupant set point preferences (set points were often observed at 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 was observed at this site, it was only 91 kWh/year, due to overall low cooling equipment usage and occupant preferences.

Additional observations include:

- Home CO and radon levels were not greatly affected (either negatively or positively), and levels basically stayed the same after the retrofits, and within recommended safety limits. Crawl space humidity levels were reduced at all four sites. During the baseline, three of the houses regularly saw RH levels exceed the recommended 70% limit. After the sealing was installed, in all conditions, crawl space RH levels were reduced below the recommended limit. 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. After measure implementation, the daily average IAT and RH levels were all closer to the typical ASHRAE comfort zone. Whether this was a result of the crawl space sealing or the new thermostats is impossible to determine. Both likely had a positive effect on comfort levels.

- We conducted successful DR simulations at two of the four sites. These tests were remote thermostat set point adjustments, by one 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 residential DR testing in other studies (Southern California Edison, 2009). Unfortunately, DR-enabled thermostats were not installed in the baseline, so we could not compare DR potential with and without the measure. We assume the added thermal mass and “stored cooling” in the crawl space would allow for more comfortable, reduced compressor cycling DR events. We observed IAT rapidly increasing during the DR tests, and we reminded occupants not to adjust the thermostats during the tests. In some cases, the occupants manually bypassed the DR tests, suggesting the increased IAT caused discomfort.

- The market size for this retrofit measure is roughly 441,600 existing SFR homes with vented, unconditioned crawl spaces in SCE territory, and 1,387,700 across California. Of these, about 66% in SCE territory and 56% in California have central air. 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 approximately 400 and 1,100 GWh/year for SCE territory and California existing homes, respectively.

- Homes with ductwork in their crawl spaces should be primary outreach targets, due to having the most energy savings potential. The market share of new construction homes with crawl spaces appears to have decreased over the last several years, but this does not necessarily imply a permanent trend.

- The average site measure cost was about $8.70 per square foot. The simple payback would occur over 30 years, based on data collected and project costs. However, despite this long payback period, there are several factors that make this measure attractive due to 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 the reduced risk of asthma (and potentially radon).

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

    - Time-Dependent Valuation (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 was concentrated during the cooling season, and appears to be well distributed throughout the day, so savings occurs during peak hours.

    - Payback would likely be better for new-construction buildings, or when work was already being performed in crawl spaces.

    - The additional crawl space cool air and thermal mass likely marginally increased 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. The customer cost is high, and the potential benefits are not well known. It is unlikely that homeowners would consider sealing and conditioning their crawl spaces when there are competing priorities with other home repair and maintenance needs. This resistance could potentially be mitigated through market outreach about the benefits and appropriateness of the 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.

Commonly-used building modeling software (such as CBECC-Res or eQuest) does not enable sealed, conditioned crawl space modeling. This market barrier must 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. Conditioned crawl space construction guides have been published, but market adoption and contractor awareness remains low (Advanced Energy, 2005). The measure could be promoted through contractor and new home builder outreach via workshops and other promotional and training programs. Builders and contractors still sometimes avoid the measure, due to the misconception 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 a variety of benefits, we recommend taking program support into consideration. Recommended courses of action to help increase market adoption include:

- Gather construction and industry professionals for a workshop, to identify opportunities for cost reduction and standardization.
- Perform a comprehensive building modeling study and a sensitivity analysis of building conditions and CZs, 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 enable baseline DR testing and help avoid changes to occupant behavior, due to improved set point control. Additionally, occupants should be screened for their HVAC use and set point preferences prior to enrollment, to avoid unusual cases such as those encountered at 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 building type with the highest savings was 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 the heating season, and this may potentially be mitigated by control strategies.
- Possible program support includes code changes, energy budgeting of new construction 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 normalized annualization at 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.

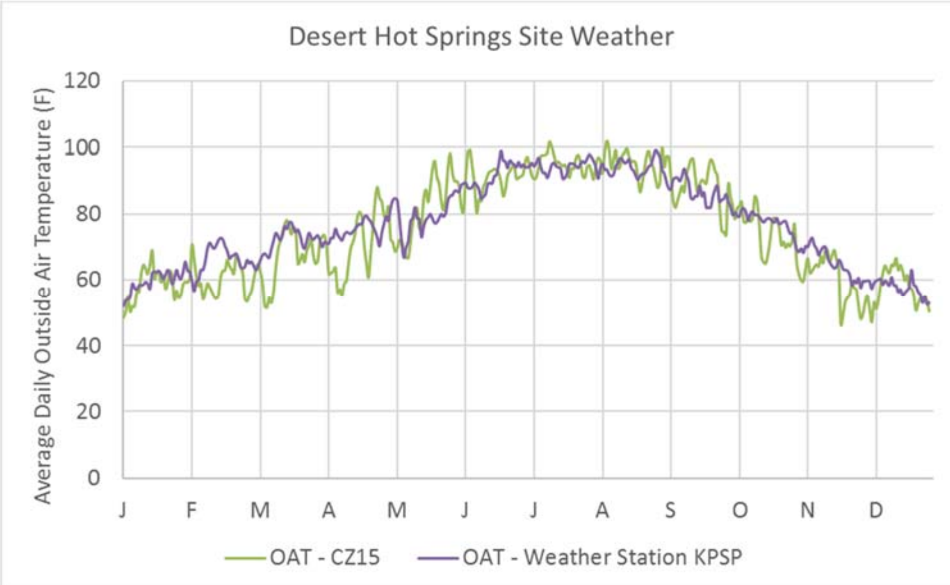

FIGURE 38 – DESERT HOT SPRINGS HOST SITE WEATHER AND CZ15

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

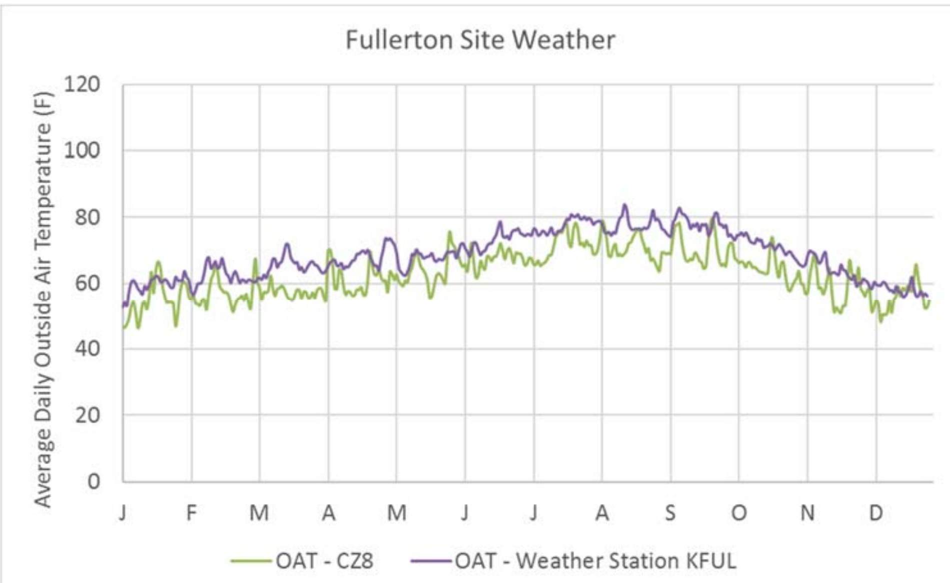

FIGURE 39 - FULLERTON HOST SITE WEATHER AND CZ8

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

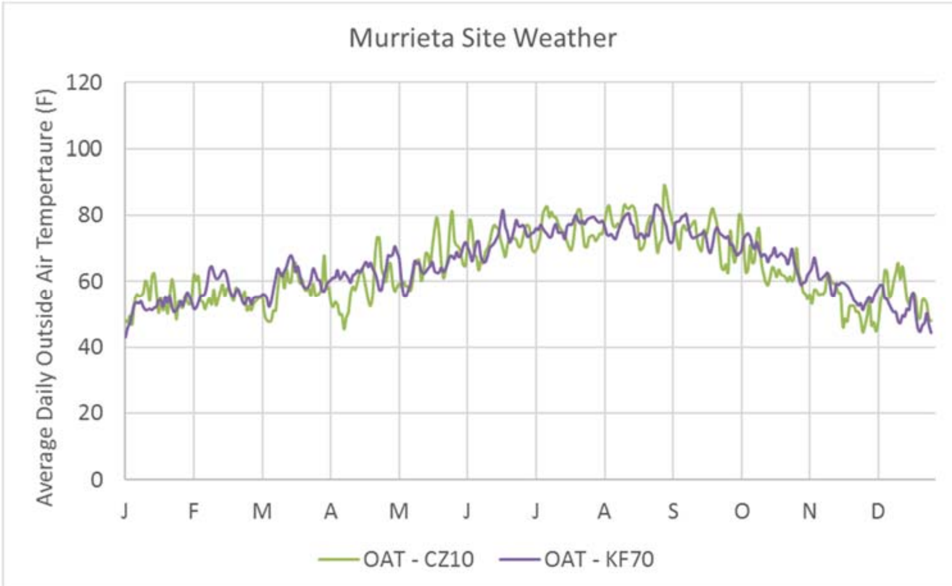

FIGURE 40 - MURRIETA HOST SITE WEATHER AND CZ10

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

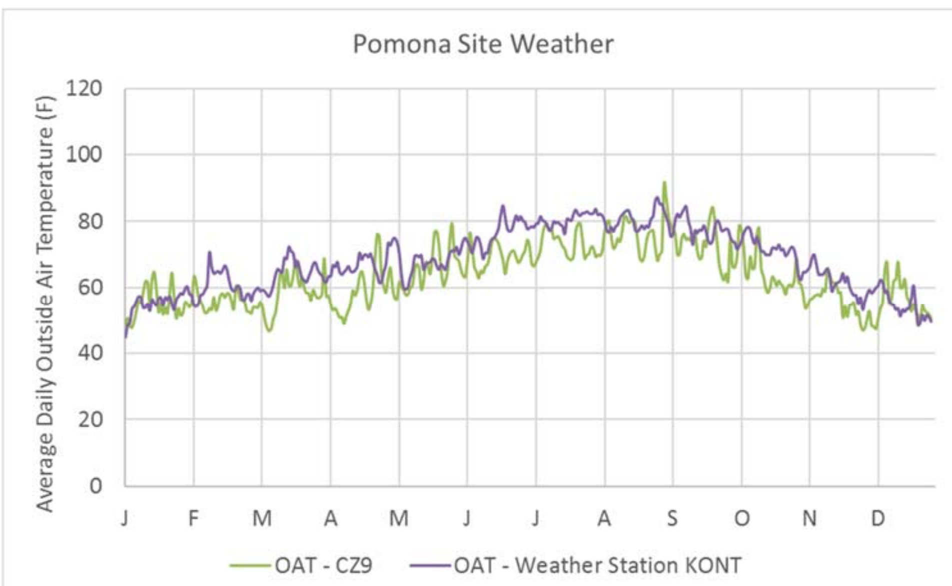

FIGURE 41 - POMONA HOST SITE WEATHER AND CZ9

APPENDIX B – MURRIETA REGRESSION ANALYSIS

Although we 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 upward 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 OATs, as shown in Figure 32. Other regression options (piecewise, linear, etc.) were tested, but all showed similar results. However, the post-measure regression basically shifted up from the baseline by about two kWh per day, and the relationship to OATs appeared to be largely unchanged.

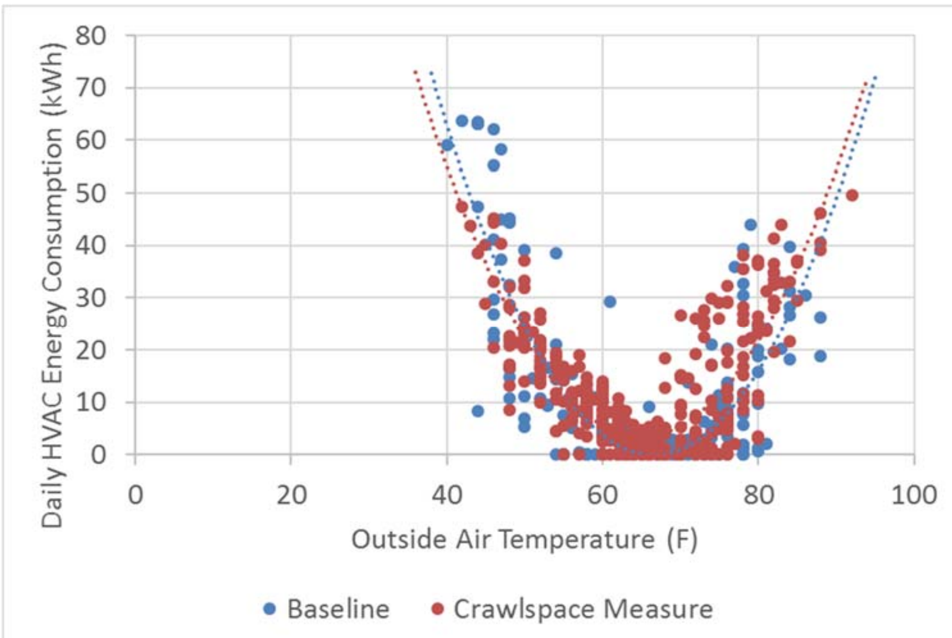

FIGURE 42 – MURRIETA HVAC ENERGY RELATIONSHIP TO OAT

In fact, the difference in normalized energy between the baseline and post-measure conditions was calculated at approximately 750 kWh in CZ10. Thus, based on this uncertainty in normalized savings and the 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 as follows:

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

TABLE 31 – 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, IAT normalization was needed, to compare across the measurement periods. When defined as IAT=f (OAT) from the baseline period, post-period comfort conditions may be modeled the same as for the baseline. Figure 13 shows that IAT can be modeled as:

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

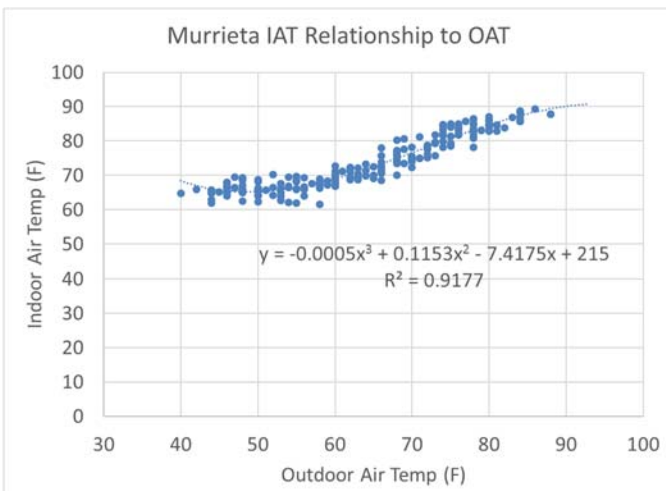

FIGURE 43 - MURRIETA INDOOR TEMPERATURE AS A FUNCTION OF OAT DURING BASELINE

Using these models, we can calculate the annual energy usage for an average host site weather year. Since we observed the average local weather station daily temperatures differed from California CZ 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.

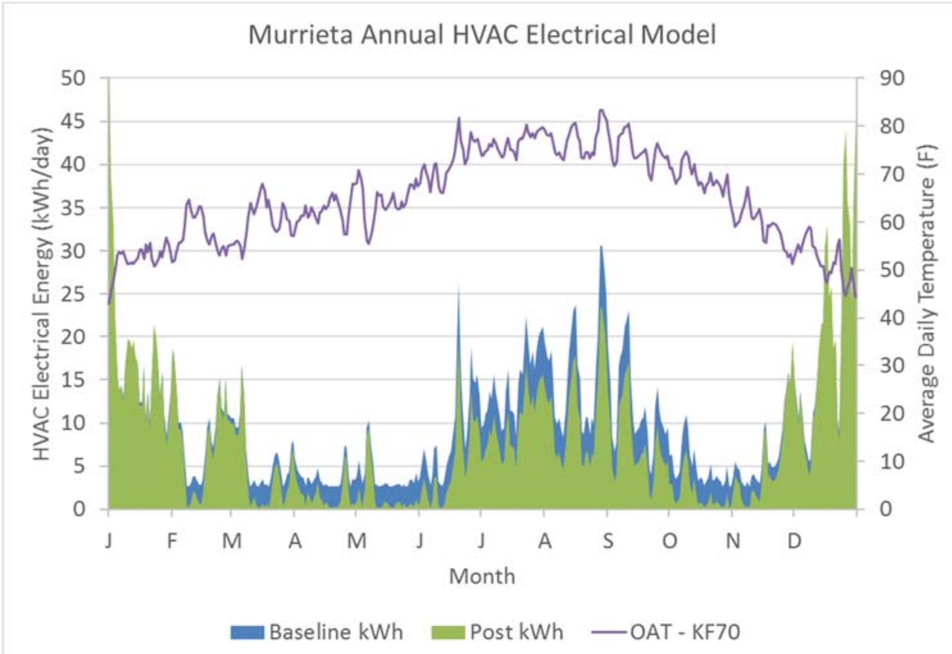

FIGURE 44 – MURRIETA ANNUAL ELECTRIC USE PROFILE

Similar calculations using CZ data can be performed to extrapolate the building type to standard California weather years. Table 32 lists the estimated energy usage and savings for each SCE CZ, and local weather data for the Murrieta building type and occupant behavior models.

TABLE 32 – 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 each case, the all-electric Murrieta site model showed energy increases for all tested climate zones. Every tested modeling method showed similar increases in energy usage. It is not clear why, especially since blower door testing showed a decrease in building leakage. However, the Murrieta site data was confounded by a few factors:

- A pre-existing crawl space vapor barrier was present during the baseline period.
- There was a measurement data gap during the baseline summer months.
- Changing occupant behavior patterns appear to have resulted in an upward shift 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.