Deep Energy Retrofits - Lessons Learned from Central Valley Research Homes

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ABSTRACT

When the Paris talks resulted in an international agreement it became incumbent for all parties to embark on activities to push to the goal. Existing homes offer a vast opportunity for reduced greenhouse gas emissions through currently available energy efficiency upgrades. However they are neither extensively nor properly implemented. The Central Valley Research Homes Project (CVRH) applied intensive research exploring these opportunities. It tested retrofits and technologies in real homes with well controlled repeatable indoor conditions. The project monitored four homes of different vintages (1948, 1953, 1996 and 2006). With these laboratories, CVRH tested currently available packages of upgrade measures for existing homes.

The project developed envelope and HVAC efficiency upgrades that saved a measured average 79% of the cooling energy in the older homes through simple retrofits including: short buried attic ducts, small AC compressors with large coils, wall and attic insulation, air sealing, high evaporator airflow, modern windows, etc. Extreme measures to bring the ducts into conditioned space were not needed. Even the 2006 home achieved a 52% cooling energy savings. That home was already well insulated, with good windows. Most of these measures would do equally well in humid climates.

This research suggests that simple checklists can determine the highest priority retrofits providing significant energy savings. Accurate checklists can deliver inexpensive guidance for retrofits in existing homes.

These measures can be used in neighborhood direct install programs. Such programs could reach a larger number of homes at a lower cost, contributing to emissions reduction goals.

Introduction

Existing homes offer a huge and virtually untapped opportunity for energy efficiency retrofits. They also can provide some of the savings needed to implement the Paris Accords. Over three years the CVRH Program applied intensive scientific research to address these opportunities on existing homes in Stockton, CA.

The field performance of a technology is often poorly characterized by laboratory testing or theoretical calculations because of inherent assumptions and missing interactions within a building. This project overcame those problems by testing the technologies in full-scale homes in a real California climate, with well controlled and repeatable indoor conditions.

There were four vintage homes in the project (1948, 1953, 1996 and 2006). Prior to any changes the project had HERS raters examine the homes to estimate anticipated "normalized" heating and cooling usage in the baseline year. These results were compared to the actual heating and cooling use "normalized" to the HERS software temperature file. The results were disappointing. The study found poor agreement between HERS cooling and heating energy use estimates and monitored energy use at the four test houses. Individual raters produced estimates as high as 6 times the monitored energy use. Even with inputs carefully validated by the study team, the simulation models overestimated cooling and heating energy use at three of four houses (Conant et al. 2015, 10).

Following the multiple HERS raters' assessments, the houses were retrofitted with the monitoring and control devices as well as "simulated occupants". The team installed reference cooling and heating systems (Reference systems) in each home. As in Figure 1, these systems are located completely indoors (except for the AC condensing unit) so no duct conduction or leakage effects occur. These Reference systems provide a nearly constant “yardstick” for changes in the building load when retrofits were introduced after the baseline year. Each Reference system alternated with the test HVAC system (House system) on two-day cycles.

Figure 1. Reference "yardstick" air conditioner cooling system and room-by-room electric resistance heating system. *Source:* R. Chitwood, pers. comm., 2012.

In Retrofit Year 1 the project installed envelope and HVAC efficiency retrofits that saved an average of 79% of the cooling energy[1] in the older three homes through simple retrofits including: short buried attic ducts, small AC compressors with large coils, wall and attic insulation, air sealing, high evaporator airflow, modern windows, etc. Even the newest home, the Caleb 2006 house, built in 2006 under the 2005 California Building Energy Efficiency Standards achieved a 52% cooling savings. It was already well insulated, with good low E windows.

Data from this experiment were used to estimate savings potential for 3.17 million single-family and duplex homes in 17 hot dry California counties.

Description of Research Homes in Baseline Year and Retrofit Year 1

The project team leased four homes in Stockton, California. The homes vintages ranged from 1948 to 2005, and varied in their foundation type, size and number of stories. The energy issues presented by the homes covered a spectrum existing houses. Glazing ranged from single-pane steel casement windows to double-pane low-E windows. Similarly, ceiling insulation ranged from R-5 to R-30. The quality of air leakage barriers, duct location and insulation, as well as HVAC systems and efficiencies provided similar ranges of energy performance.

These homes are identified by their streets and vintages: Grange 1948, Mayfair 1953, Fidelia 1996 and Caleb 2006. Each house was controlled with respect to thermostat settings, internal gains and whole house fan operation as defined in California's Title 24 Residential ACM Manual (CEC 2008a).

[1] The cooling savings calculation is the difference between the baseline year AC use and the retrofit year AC use minus the electricity used by the whole house fan and IAQ fan(s).

Grange 1948

Built in 1948, the Grange Avenue house is the oldest house. At 848 ft^2, it is the smallest. It is a two-bedroom, single-story rectangular slab on grade house. Grange 1948 had an initial annualized cooling energy use of 1.05 kWh/ft^2, 42% higher than Caleb 2006. Grange 1948 had an annualized heating energy use of 0.38 therms/ft^2, 4.8 times that of Caleb 2006.

The baseline conditions included single-glazed aluminum slider windows (Figure 2), a virtually uninsulated ceiling (Figure 3), and unusual 2 x 3 walls with the same accordion aluminum foil insulation as the ceiling. There was an 80.5 AFUE 50,000 BTU/h input furnace and AC coil in the garage. The ducts were in the attic and the AC was a 2.5 ton 10.45 SEER 9.5 EER roof-mounted condensing unit.

Figure 2. Grange 1948 aluminum slider windows.
Source: R. Chitwood, pers. comm., 2012.

Figure 3. Grange 1948 attic accordion foil insulation and long HVAC return system strapped to rafters.
Source: R. Chitwood, pers. comm., 2012.

The house duct system had a long branched supply duct system and a long return system. The return duct was 38.8 feet long stretching from the central hall to the garage. The layout is shown in Figure 4. The total surface area of the duct system was 352 ft^2 (41% of the floor area).

In retrofit year 1, to reduce conduction losses and improve airflow, the return was shortened to 5 ft. and the supplies replaced with a single 14 in. diameter trunk duct to a delivery box in new dropped ceiling in the hall. Conditioned air was run through short ducts within the dropped ceiling to each room. Except for the short return and the trunk line to the dropped ceiling, all ductwork was in conditioned space. The single supply trunk in the attic was R-8 flex duct buried in the new attic insulation. The new duct design is shown in Figure 5. This retrofit is identified as measure ID 7.

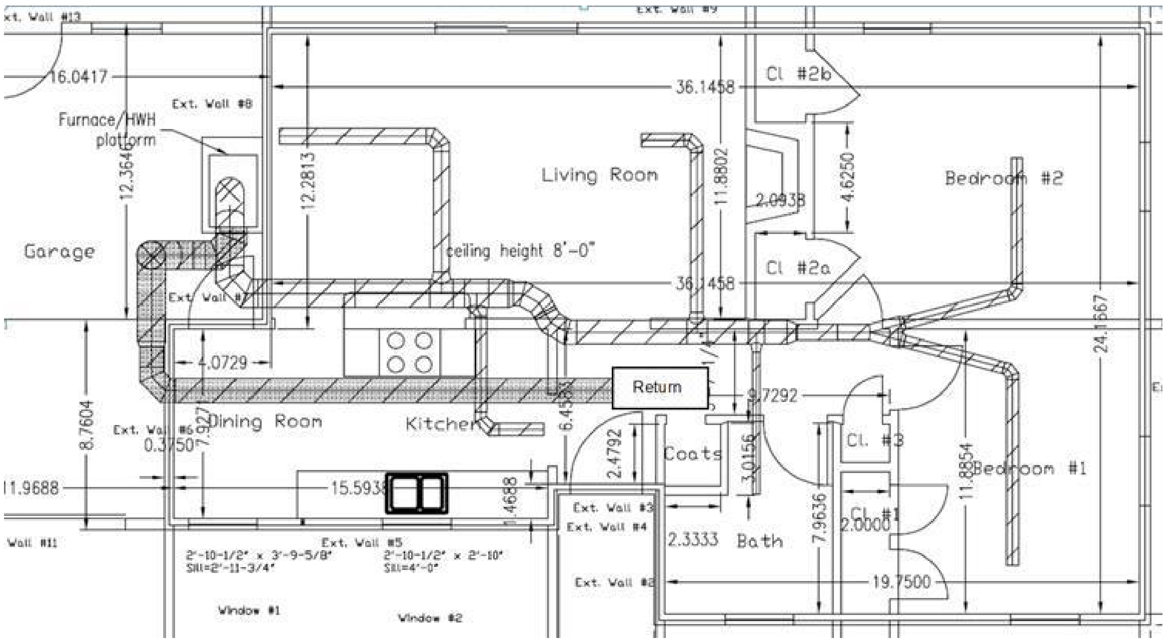

Figure 4. Grange 1948 original high surface area duct layout. *Source:* R. Chitwood, pers. comm., 2016.

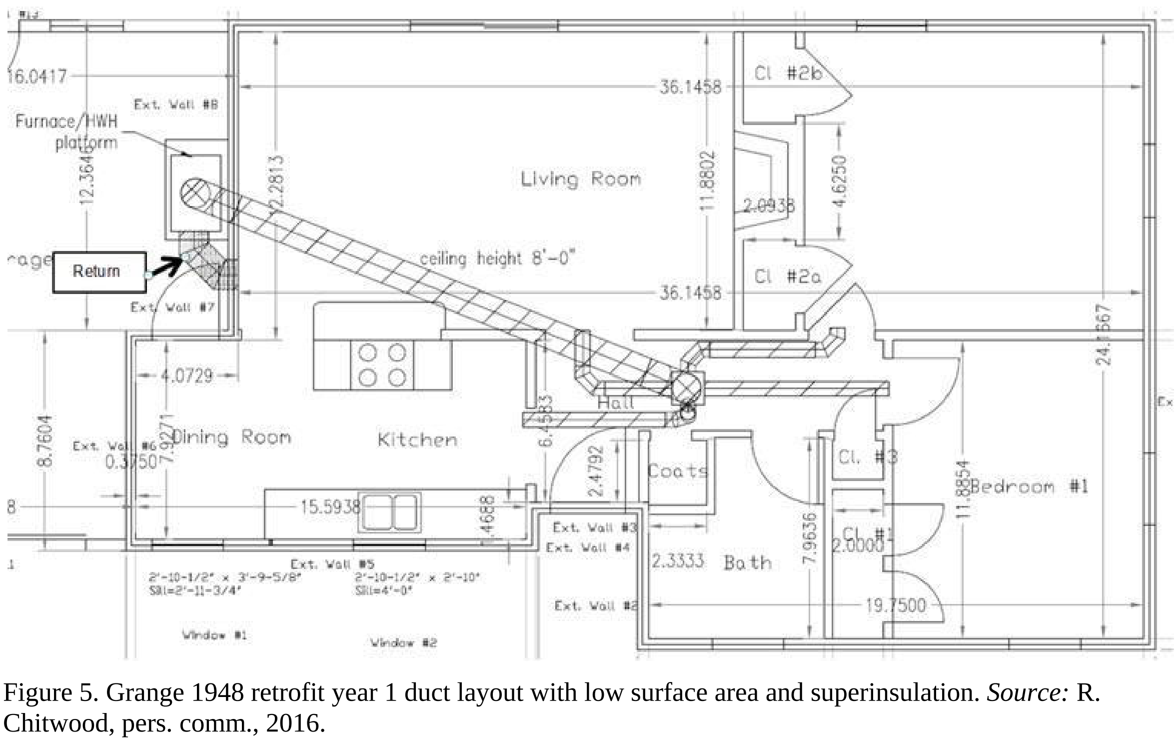

Figure 5. Grange 1948 retrofit year 1 duct layout with low surface area and superinsulation. *Source:* R. Chitwood, pers. comm., 2016.

The baseline configuration and the retrofits to Grange 1948 are detailed in Table 1.

Table 1. Grange 1948 baseline conditions and year 1 retrofit measures.

Measure and ID Number	Baseline Condition	Year 1 Retrofits
1 Air Leakage		
Attic to House Leakage	Multiple leakage areas to the attic, including chimney and garage.	Air sealed between conditioned space and attic and between attic and garage.
Attic to Garage Leakage	Open	Sealed
House Leakage	762 CFM50 (6.7 ACH50)	438 CFM50 (3.8 ACH50)
2 Attic Insulation (852 ft^2)	Two layers of foil paper, approximately R-5	Removed and added R-49 loose-fill fiberglass
3 Attic Ventilation	3.5 ft^2 of venting (1 to 242)	15.5 ft^2 of venting (1 to 55) to accommodate whole house fan airflow out through the attic
4 Wall Insulation	Foil paper insulation in 2 x 3 walls, 960 ft^2 net wall area, ~ R-5	Drilled and filled to R-10 with loose-fill fiberglass
5 IAQ Ventilation	None	ASHRAE 62.2 compliant ventilation system – Panasonic Whisper Green™ bath exhaust fan, 39 CFM, 5.5 watts.
6 Windows (78 ft^2)	Aluminum, single-pane, NFRC U 1.1	Vinyl, double-pane, low-E2, U 0.30, SHGC 0.25
8 Air Conditioning System	2.5 ton York H2RA030S06G, Coil ICP EPD30B15B1	Replaced compressor only (1 ton) Tecumseh RKA5512EXD (EER 11.09). Installed with TXV adjusted to 6ºF system superheat.
AC Rated Efficiency	10.45 SEER (9.5 EER)	No rating on new system, compressor EER 11.09
AC Size	2.5 tons	1+ Ton
AC Airflow	219 CFM per ton	540 CFM per ton
Static Pressure	Total 1.13 IWC	Total 0.28 IWC
Fan Motor	1/3 HP PSC	Variable HP Concept3™ BPM
Fan Watt Draw	361 watts	80 watts
9 Heating System	50,000 BTU/h 0.80 AFUE gas furnace	Reorificed to 29,700 BTU/hr.
10 Outside Ventilation for Cooling	None	Two whole house fans total 1105 CFM into the attic. On from dawn to 11 PM if the outside temperature was 9ºF below inside and inside was >68ºF. The combined power 141 watts.

Source: R. Chitwood, pers. comm., 2012. R. Chitwood, pers. comm., 2013.

The duct system revisions are detailed on the previous pages. The retrofits in all of the houses are generally not new inventions, but rather proper application of known measures. Many of them could be considered "emerging" since they have a very very small market share. It is not radical to reduce the size of the air conditioner compressor compared to the AC coils. For years the manufacturers have increased the efficacy of the coil heat exchange by improved designs and larger surface areas. This effectively reduces the size of the compressor relative to the heat exchange coils. It has long been known that most air conditioners are significantly oversized (James et al. 1997), but studies have been inconclusive concerning the energy savings associated with downsizing air conditioners (Sonne, Parker, and Shirey, 2006). One of the reasons that the downsizing savings have been small (or negative) is that smaller air conditioners with current attic duct designs run longer cycles, resulting in more duct conduction losses. This project downsized only the compressor (thus providing relatively larger coil areas). **Simultaneously** it reduced the surface area of the ducts in the attic, placed them on the ceiling joists, and buried them in insulation (thus massively reducing the duct UA and reducing duct conduction losses). The smaller AC sizes also resulted in large gains in evaporator air flow per ton. This increases the sensible efficiency of the unit as needed in hot dry climates.

Figure 6 shows the Grange 1948 baseline and retrofit year 1 Reference system cooling energy use vs. outdoor temperature. This shows shell, whole house fan, and IAQ effects.

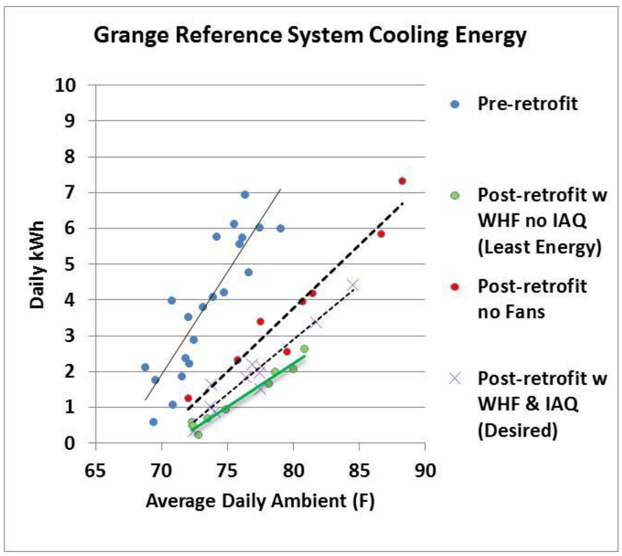

Figure 6. Grange 1948 baseline and retrofit year 1 cooling energy usages showing shell improvement effects.
Source: Proctor, Wilcox, and Chitwood 2016a.

Mayfair 1953, Fidelia 1996, and Caleb 2006

The baseline configuration and first year retrofits are detailed in Proctor, Wilcox, and Chitwood (2016a). These three houses followed similar retrofit paths as Grange 1948 eliminating only the measures that were already present in each house. There are exceptions described later.

Mayfair 1953 is a three-bedroom 1,104 square feet home. It is a one-story rectangular building over a crawlspace. On the surface this house presented fewer opportunities than Grange 1948. It had an initial annualized cooling energy use of 0.90 kWh/ft^2, only 22% more than the newest home. However, it had a 0.29 therms/ft^2 heating energy use.

Fidelia 1996 is the second newest test home. At 1,690 ft^2, it is also the second largest home. It is a two-story home with slab on grade construction. Four bedrooms are downstairs. Its complicated footprint and numerous angles make insulation and other construction errors likely.

In spite of being less than 20 years old, this house had a disappointing annualized cooling usage of 1.07 kWh/ft^2, essentially equivalent to the 1948 Grange 1948 house with the foil insulation. It had a heating energy intensity of 0.15 therms/ft^2.

Caleb 2006 is the newest and largest (2,076 ft^2) of the houses. It is a two-story rectangular home with a partial tuck-under garage. It has low-E double-pane windows. The zoned HVAC equipment and ducts are in the attic under a tile roof. This house is similar to the 2008 California Title 24 code and provides the greatest challenge to procuring retrofit savings. Its ft^2 initial annualized energy intensities were: 0.74 kWh/cooling, 0.08 therms/ft^2 heating.

The baseline configurations and retrofits to these three houses are summarized in Table 2.

Table 2. Mayfair 1953, Fidelia 1996 and Caleb 2006 baseline and year 1 retrofit measures.

	Mayfair 1953	Fidelia 1996	Caleb 2006
Measure & ID	Baseline *(Retrofit)*	Baseline *(Retrofit)*	Baseline *(Retrofit)*
1 Air Leakage	1437 CFM50 *(1362 CFM50)*	1626 CFM50 *(1168 CFM50)*	1494 CFM50 *(1615 CFM50)*
2 Attic Insulation	R-7 *(R-49)*	R-30 *(R-49)*	R-30 *(No change)*
3 Attic Ventilation	1 to 148 *(1 to 55)*	1 to 385 *(1 to 85)*	1 to 154 *(1 to 66)*
4 Wall Insulation	None *(R-13)*	R-13 *(No change)*	R-17 *(No change)*
5 IAQ Ventilation	None *(50 CFM)*	None *(57 CFM)*	None *(64 CFM)*
6 Windows	Steel cas'mnt 1 pane *(Vinyl, double,lowE^2)*	Aluminum 1 pane *(Vinyl, double,lowE^2)*	Double pane low E *(No change)*
7 Duct System	New convoluted R-8 with 113' return *(Low restriction low surface area buried in attic insulation with 21'return)*	Convoluted long ducts in the attic R-4.2 *(Low restriction low surface area all out of sight in conditioned space R-8)*	Two zone dampered R-6 *(Same ducts reconfigured to "capacity shift zoning")*
8 Air Conditioning System	New 13.2 SEER 2.5 ton package roof top 365 CFM per ton *(Installed 1.5 ton compressor in unit 612 CFM per ton)*	3.5 ton 10 SEER 390 CFM per ton *(Installed 1.4 ton 16 SEER heat pump locked on low speed EER 12.65 542 CFM per ton)*	4 ton 10 SEER 215 CFM per ton with single zone on *(Installed 2.5 ton outdoor unit only 443 CFM per ton with single zone on)*
9 Heating System	80.5 AFUE rooftop *(derated by 36%)*	80 AFUE furnace *(3.67 COP heat pump)*	80 AFUE furnace *(No change)*
10 Outside Ventilation for Cooling	None *(1520 CFM whole house fan venting)*	None *(1593 CFM whole house fan venting)*	None *(2075 CFM whole house fan venting)*

Capacity shift zoning never eliminates flow to a particular zone, rather it shifts a portion of the capacity from zone to zone. *Source:* R. Chitwood, pers. comm., 2012. R. Chitwood, pers. comm., 2013.

Special cases

Mayfair 1953 had a ventilated wet crawlspace due to a faulty irrigation system design. In the first retrofit year the irrigation system was removed and the downspouts were extended eliminating the problem.

Caleb 2006 had roof tiles. In the first retrofit year the tiles were removed and reapplied with PolySet spray foam for some roof deck insulation.

Monitoring and Control Systems

The monitoring and control systems control the HVAC and internal gains and allow for switching between the House and Reference HVAC systems.[2] The team heavily instrumented the research homes to provide hourly and minute by minute data. The equipment also controlled the humidifiers and heaters that simulated latent and sensible heat gain from typical occupancy (CEC 2008b, 4.7).

Monitored data points were read every 20 seconds and the averages (or sums as appropriate) were recorded every minute. There were up to 131 data points recorded every minute. These included: energy use, occupancy kWh, inside and outside temperatures, inside and outside humidities, solar radiation, wind speed, house AC temperatures (refrigerant and air), reference AC temperatures (refrigerant and air), house and reference AC condensate, garage, attic and crawlspace temperatures, high and low inside outside pressure differentials, etc.

The houses were "occupied" by heaters and humidifiers that were consistent in adding sensible and latent internal gains. The gains were derived from California's Residential Building Energy Efficiency Standards (Title 24, Part 6) as specified in the Residential ACM Manual (CEC 2008a, 3.2.5). The simulated occupants practiced the thermostat settings defined in Title 24. The thermostat settings displayed in Figure 7 produce load patterns similar to an average of California residences.

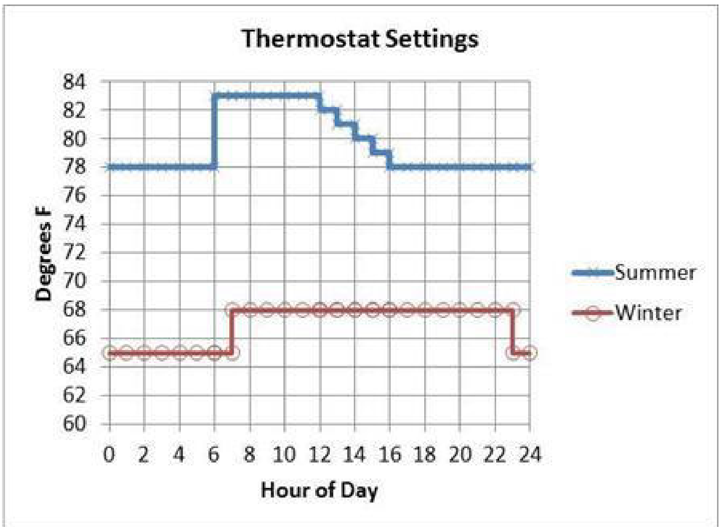

Figure 7. Thermostat settings to duplicate average California residential load shape. *Source:* CEC 2008a, 3.2.5

[2] These controls also provided switching between on and off states for the IAQ fans and the whole house fans. These items were tested in flip/flop experiments.

Impact of Efficiency Retrofits on Energy Use

From July 2012 the four houses operated with their existing envelopes and HVAC systems (baseline). Retrofit installation began in spring 2013. In retrofit year 1 the internal gains and thermostat schedules remained as in the baseline year. The Reference HVAC systems and now-retrofitted House HVAC systems alternated every two days. Monitoring for retrofit year 2 began in spring 2014. The retrofit year 2 measures were variable compressor speed heat pumps (VCSHPs), expanded whole house fan parameters and additional IAQ fan options. The systems alternated as before, but constant heating and cooling setpoints were used (no hourly changes).

Method

As detailed in Proctor, Wilcox and Chitwood (2016a), multivariate regression fits to the daily monitored data estimated the usages. Separate regressions were done for the Reference systems and the House systems. A number of potential models were tested that included the following predictor variables: Daily average ambient temperature, Average incident solar radiation, Average wind speed, Post retrofit (0/1), Post retrofit daily average ambient temperature (0/1 x ºF), Whole house fan on (0/1), Whole house fan on daily average ambient temperature (0/1 x ºF), IAQ fan on (0/1), IAQ fan on daily average ambient temperature (0/1 x ºF). These variables were tested in combinations and transformations to allow non-linearity. The final analysis used all of the above except wind speed and incident solar radiations. They used no transformations or combinations. The results were annualized to the 2013 Title 24 Sacramento weather files (1422 CDD_{63}) (CEC 2013).

The savings associated with the building shell retrofits and other load changes (whole house fans and IAQ fans) are estimated from the Reference systems' regressions. The savings from the HVAC retrofits and the load changes together are estimated from the House systems' regressions. The savings from the HVAC retrofits alone are estimated by the equation:

$$Sav_{HVAC} = 1 - \frac{RelEff_{post}}{RelEff_{pre}} = 1 - \frac{\left(\frac{UseHouseSystem_{post}}{UseRefSystem_{post}}\right)}{\left(\frac{UseHouseSystem_{pre}}{UseRefSystem_{pre}}\right)}$$

Cooling Results

Table 3 shows the efficacy of the House cooling system relative to the Retrofit cooling system in the Baseline and First Retrofit years.

Table 3. Relative cooling efficacy.

Metric	Grange 1948	Mayfair 1953	Fidelia 1996	Caleb 2006
House System Efficacy Baseline Year	57%	61%	40%	53%
House System Efficacy Retrofit Year	84%	91%	117%	73%

House system efficacies (relative efficiencies) are the House system use divided by the Reference system use.
Source: Proctor, Wilcox and Chitwood 2016a

The cooling savings from the first year retrofits are shown in Figure 8.

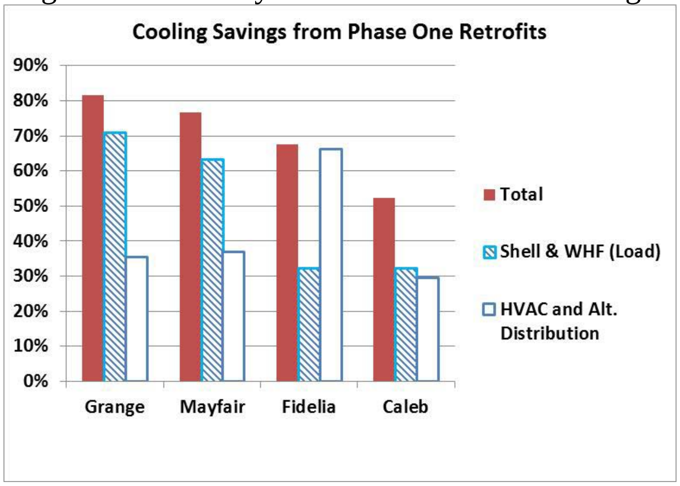

Figure 8. Retrofit Year 1 Cooling Savings. *Source:* Proctor, Wilcox, and Chitwood 2016a

With the exception of Mayfair 1953 in the House system mode, all operations indicate that the whole house fans significantly reduced the cooling from 22% to 46%. These reductions are on houses with significantly reduced total cooling load. When applied to houses with larger cooling loads, the percentage savings may be less.

Combining whole house fan savings with insulation, strategic air sealing, and high efficiency windows, the net cooling loads were reduced by 71% in Grange 1948 and 63% in Mayfair 1953 (the two older homes with poor insulation) and by 32% in the newer homes.

Putting the ducts in conditioned space has been the Holy Grail of ducted heating and cooling systems for some time, but CVRH has proven that the ducts do not have to be in conditioned space to achieve high efficiencies. The two older CVRH homes had their attic duct systems shortened, sealed and superinsulated with results comparable to conditioned space ducts.

The Hot Dry Air Conditioning systems (HDAC) reduced duct restrictions and compressor sizes in all four homes. This increased the cooling coil airflow from an average 297 CFM per ton to an average 534 CFM per ton. The combination of increased duct efficiency, increased cooling air flow, and increased heat exchange efficiency significantly improved cooling efficiencies and produced peak reductions in all four homes.

Heating Results

Table 4 shows annual heating savings estimates from the first retrofit packages.

Table 4. Heating system efficiency and savings.

Metric	Grange 1948	Mayfair 1953	Fidelia 1996	Caleb 2006
House System Efficiency Baseline Year	65%	83%	60%	75%
House System Efficiency Retrofit Year	68%	83%	3.81 COP	72%

House system efficiencies are the percent of Reference system use. *Source:* Proctor, Wilcox and Chitwood 2016a

The net heating savings from the first year retrofits are shown in Figure 9.

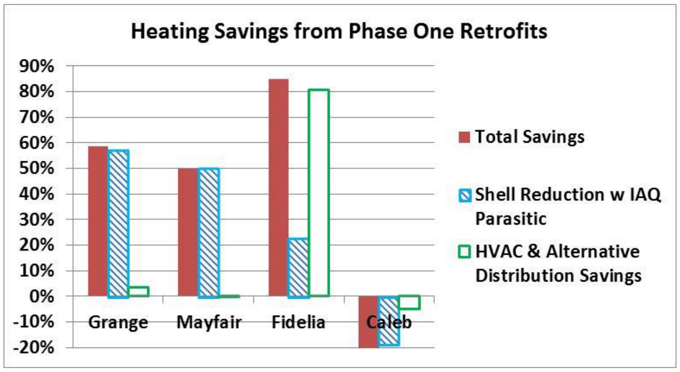

Figure 9. Year 1 Heating Savings from Shell and Mechanical Retrofits. *Source:* Proctor, Wilcox, and Chitwood 2016a

The two older house shell retrofits reduced the heating load by an average of 54%.

While the envelope retrofits on Caleb 2006 reduced cooling consumption, they had a negative effect on the heating load due to increased infiltration and reduced attic temperatures. In Fidelia 1996 the gas furnace was replaced with an electric heat pump. The site energy heating usage savings at Fidelia 1996 was 85%.

Impact of Variable Compressor Speed Heat Pump (VCSHP) Retrofits on Energy Use

In retrofit year 2, Variable compressor speed heat pumps (Mini and Multi-splits) were installed in Grange 1948, Mayfair 1953 and Caleb 2006. This research is detailed in Proctor, Wilcox, and Chitwood (2016b) and Proctor (2015). The unit installed at Caleb 2006 was a manufacturer's experiment using commercial sized systems that were too large for the house. The Grange 1948 and Mayfair 1953 systems were bought at local retailers and installed by contractors who were reported to be competent in their installation. The monitored cooling energy use was compared to the reference air conditioners with conditioned space ducts. Heating use was compared to the reference electric resistance heaters.

Monitored performance in cooling. Seasonal Energy Efficiency Rating (SEER) is the primary energy descriptor required by Federal standards for labeling residential cooling systems, higher ratings indicating a more efficient system. Systems with higher SEERs are generally believed to produce cooling energy savings defined by:

$$\%Savings = \frac{(SEER_{high} - SEER_{low})}{SEER_{high}}$$

The Grange 1948 and Mayfair 1953 VCSHPs have SEERs above 21, and should use significantly less cooling electricity than the reference systems (SEER 14 and 16 respectively). The SEER tests are completely different for VCSHPs and conventional single speed ACs (such as the reference systems). This experiment identified the incompatibility of the two different SEERs. Figure 10 compares the anticipated savings based on rated SEER to the actual savings. The VCSHPs all saved less electricity than expected and two provided negative savings. All three VCSHPs use more energy than the lower rated conventional systems. One cause is constantly operating evaporator fans. However, Caleb 2006 and Grange 1948 seriously underperform even with the constant evaporator fan kWh removed.

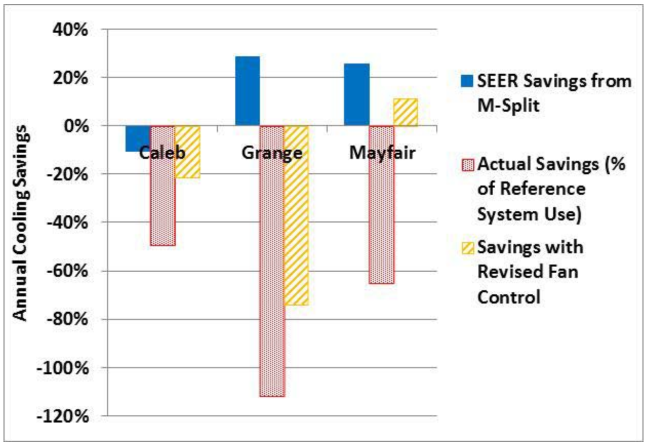

Figure 10. VCSHP Cooling Savings (Loss) in Year 2.
Source: Proctor, Wilcox, and Chitwood 2016b

Monitored performance in heating. Figure 11 compares the monitored savings with the anticipated savings based on the heat pump rated Coefficient of Performance (COP) relative to the reference electric resistance heating. The units at Caleb 2006 and Grange 1948 seriously underperform their ratings even with the most beneficial fan control settings

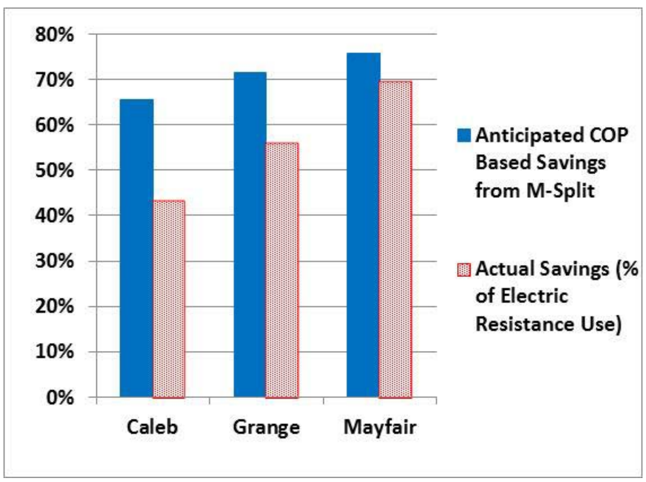

Figure 11. VCSHP Heating Savings in Year 2. *Source:* Proctor, Wilcox, and Chitwood 2016b

Results and Conclusions

1. Existing homes offer a vast opportunity for reduced greenhouse gas emissions through currently available energy efficiency upgrades. These simple, available retrofits (whole house fans, duct reconfiguration, AC modification, insulation, air sealing, modern windows, etc.) are neither extensively nor properly implemented as retrofits. These envelope and HVAC efficiency upgrades produced an average 75% cooling savings in the three older homes and 52% on the newest house.

2. The AC systems were revised to be appropriate to hot dry climates by raising the system sensible EERs. These revisions included: small compressors, large coils, high CFM per ton, shorter ducts, ducts on ceiling joists and buried in insulation or moved to drop ceilings with short supply runs. The HVAC measures alone improved average House system efficiency by 74% (efficacy difference / baseline efficacy).
3. Shell retrofits combined with whole house fans reduced the net cooling loads by 71% at Grange 1948, 63% at Mayfair 1953 by 32% at Fidelia 1996 and Caleb 2006. The whole house fans accounted for 22% and 13% respectively of the shell reductions at Grange 1948 and Mayfair 1953 (the older houses). They accounted for 46% of the shell reduction at Fidelia 1996 and up to 75% of shell reduction at Caleb 2006.
4. The shell retrofits reduced the heating loads in the two older houses by an average of 54%. While shell retrofits on Fidelia 1996 netted a 23% load reduction and Caleb 2006 had an increased heating load due to increased infiltration and lower attic temperatures
5. There was poor agreement between HERS cooling and heating energy use estimates and monitored energy use at the four test houses. Even with carefully validated inputs the simulation models overestimated cooling and heating energy at three of four houses.
6. Simple checklists rather than simulations can determine the highest priority retrofits that provide significant energy savings. Such inexpensive guidance used in neighborhood direct install programs could reach a larger number of homes at a lower cost, contributing to emissions reduction goals.
7. Variable compressor speed heat pumps (VCSHPs) have potential to provide improved energy efficiency. However, the anticipated improvements in efficiency were not realized in the three test homes. The controls and control interfaces on these are complex and can lead to significant increases in cooling energy use. Continuous operation of the inside fans are problematic.
8. The VCSHPs' SEERs, HSPFs, EERs and COPs are not comparable to single speed machines. Relative ratings should not be used to estimate savings from these systems. (Ecotope 2011) and others quoted in Proctor, Wilcox, and Chitwood (2016b). Simultaneously, no consistent or achievable field verification tests can assure contractors, technicians, inspectors or regulators that VCSHPs are operating as rated.

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