The Field Hand and the California Model: An Example of Blending Operational Measurements with Performance Models

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ABSTRACT

This paper describes the analytical process and results of a metering study of more than 150 residential participants in utility programs focused on early replacement of air conditioning (AC) with high efficiency systems. This metering study is one of the largest performance measurement efforts to date to monitor efficiency in addition to energy consumption. The study employs new data analysis methods supporting examination of site metered data for large samples in a cost effective manner. This work was particularly challenged because the measurement process began after the replacement event; only the post-replacement performance could be monitored.

Savings were calculated as the difference between the actual monitored post-replacement performance and a hypothetical baseline developed from monitoring other units. The differences were applied to samples of residential stock that were considered similar to the pre-retrofit stock. A fortunate finding in this work has been that the empirical efficiency measurements are readily comparable to the detailed efficiency employed in the eQuest energy simulation models used to develop results for the Database for Energy Efficient Resources database. In this work the DEER models' derived efficiencies can be used as estimators of upper bound performance.

Results of this work show that units meeting the code requirement of SEER 13 do not meet expected efficiency performance levels, and prior estimates of the cooling load for mild regions are too high. This work demonstrates a methodology that can develop detailed site monitoring data into annual energy and demand savings estimates, which is also compatible to, and consistent with, the existing DEER energy simulation modeling approach.

Introduction and Project Summary

This work was conducted as part of an impact evaluation of 2006-08 HVAC programs of several California utilities, conducted for the California Public Utilities Commission (CPUC). These HVAC programs sought to save energy by encouraging the use of new efficient HVAC units that met or exceeded code. Two incentive-options were available to eligible customers.

1. If an HVAC unit fails and needs replacement, then replace it with a unit that exceeds the current SEER 13 code requirement. This option is referred to here as replace on burnout, ROB.

2. Replace an older unit preemptively with a new code-compliant, referred to here as early replacement, ER.

Programs of this type can have broad impact and were therefore classified as "high impact measure" (HIM) programs in the CPUC impact evaluations. The evaluation applied to these high impact measures was subjected to a heightened level of scrutiny. The objective in this paper is to present a brief discussion of the methodology and results as applied in the residential sector. (The programs and the associated evaluation monitoring applied to both the residential and commercial sectors, but it is well beyond the limits of this paper to discuss both sectors.)

Although the detailed methodology of this work and the results are presented in the final HVAC report on the CPUC Energydataweb website, there is no indication of the uniqueness and versatility of the empirical approach that was applied in this work vis-à-vis other evaluation approaches. In fact, this is one of the largest full monitoring exercises (commercial and residential) ever applied to HVAC installations. As such, the scale of this operation was too large to permit the detailed treatment that would have been applied in a full research context and the evaluation was not intended to be a full research project. Early drafts of the monitoring plan contemplated the use of eQuest models for every site in order to provide the hourly energy use estimates required for the evaluation of HIM measures. But it was quickly apparent that the data collection and analysis overhead were out of scale with the project budget. Therefore, Cadmus devised a method that was more cost effective than a research approach and that was adaptable to semi-production level full monitoring required for rigorous M&V-based HIM evaluation.

This work is the first application of this new method. There have been many applications of rigorous monitoring applied to operating HVAC systems, such as the recent ADM work in California conducted for SCE and ASHRAE (ADM 2009). These applications are highly detailed but stop short of making rigorous annual savings estimates. The utility and novelty of the method applied in this evaluation is that it can develop annual energy savings and peak demand savings estimates from a limited set of field monitoring data consistent with the rigor of the HIM M&V requirements. An added benefit of this approach is that it is also consistent with, and easily comparable to, the detailed HVAC efficiency estimates used in the development of DEER results.

Selection of Base Cases

The performance measurement approach commonly attributes savings as the difference in the weather normalized annual energy use for the pre-retrofit and post-retrofit situations. In this case, the circumstances precluded any possibility of pre-retrofit measurements. Therefore, the analysis plan was structured to calculate a reasonable estimate of the savings in the absence of site level pre-retrofit data.

A second challenge to this analysis lay in the particular nature of the measures. The installation of a new code compliant HVAC unit is associated with the code requirements that the ducts be upgraded and tested, that the refrigeration charge be correct and that the unit be resized if necessary. These additional code requirements are all intended to increase the overall energy savings of the system in addition to the savings of installing the more efficient unit. These other code required measures, particularly duct sealing and refrigerant charge correction, are independent measures which could easily confound any estimates of the benefits of higher HVAC efficiency alone. Other studies have shown a generally poor compliance rate for these code measures, but they are a known part of the problem.

Given these formidable constraints, an M&V plan was devised which focused on developing appropriate base case performance as a stand-in for the missing pre-retrofit information. The M&V plan also defined the scope of the measurements applied to the performance of the HVAC unit replacement alone, explicitly not including the effects of the associated code-required measures that may have been applied, but for which the researchers had no data. Savings identified through this study will be lower than savings that could have been realized if all the additional code measures were applied. This restriction of the measurement to focus on the HVAC unit alone played a strong role in the selection and development of the base cases.

The initial approach for residential units involved developing a base case using well known engineering and performance specifications that apply to residential scale HVAC installations, and are embedded in the eQuest energy simulation models used to develop results for DEER. Such a prediction would only be applicable to a properly performing unit, as expected with factory-specified amounts of refrigerant charge and airflow (RCA). This is a reasonable choice since the intended savings measurement had been restricted to savings above and beyond the savings attributable to any adjustments to RCA. While such a base case may use sound engineering, it is almost entirely theoretical without any empirical roots. Therefore, as a limited empirical check, two samples of data from sites considered similar to the intended base cases were drawn from similarly monitored sites in other programs.

The first baseline efficiency sample in the ER base case consisted of 25 sites with typical units as found after an RCA treatment. These sites were considered a reasonable comparison base case for the ER participants because they represented HVAC stock, were not likely to have refrigeration charge errors, and would lead to the desired savings measurement of the HVAC efficiency savings alone, without including the co-mingled effects of charge correction.

The second baseline efficiency sample, also consisting of about 25 sites, was drawn from the monitored early replacement sites with known SEER 13 units. This sample was considered a reasonable comparison base case for the ROB participants that installed units with an efficiency greater than SEER 13.

Analysis of both baseline efficiency samples showed considerably less efficient performance than was expected by the theoretical considerations. It is reasonable to expect that various field conditions can result in less than the ideal performance. These (albeit small) samples were developed into the base cases that were ultimately used in this analysis. This overview discussion of the base case development anticipates use of the methodology described below.

Site Specific Monitoring and Analysis Methodology

The site specific analysis ultimately estimates annual energy use. The first step in this process is site monitoring.

Site Monitoring

The monitoring scheme is focused on measuring an energy balance of the air side of the unit. This requires measurement of the variables listed in Table 1.

Table 1. Logged Site Measurements

Measurement	Logging interval	Units	Derivative measurements
Outdoor unit electric energy	1.5 minutes	Pulse counts converted to Wh/interval	Maximum hourly power, hourly cooling duty cycle and energy by cooling stage
Outdoor air temperature and RH	1.5 minutes	Deg F, % relative humidity	
Indoor temperature and RH	3.5 minutes	Deg F, % relative humidity	
Return air temperature and RH	5 minutes on early data 2 minutes on later data	Deg F, % relative humidity	Average return air temperature and RH by cooling stage
Supply air temperature and RH	5 minutes on early data 2 minutes on later data	Deg F, % relative humidity	Heating duty cycle and average supply air temperature by cooling stage

Note in Table 1 that four key temperatures (and relative humidity) are measured: outside air relative humidity, return air, mixed air and supply air. The total true power at the outdoor unit is also measured. Data loggers collected these data on intervals of the order of a few minutes, for one to one and a half months, providing a direct energy use measurement for a significant portion of the cooling season.

In addition to the logged measurements, single measurements of air flow and fan power were taken, but the flow rate and indoor fan power were not logged. Monitored data were converted to hourly averages for use in the analysis. Some measurements taken at 1.5 minute intervals were also used in the analysis, including the maximum power in each hour. Taken together, this group of measurements is comprehensive enough to make an estimate of the thermal output of the unit represented in common fashion as:

Thermal output, BTU/hr =
flow, BTU/hr/deg F(return air enthalpy, BTU/lb-supply air enthalpy, BTU/lb)*

The thermal output is commonly based on the difference in the mixed air and supply air enthalpies, but in the case of residential units, there was no outside air admitted, and the thermal output could be calculated from the return and supply enthalpies. (Commercial packaged unit monitoring was more complicated because of the need to include mixed air temperature measurements. Measurement of this thermal output is typically quite challenging in commercial units because the mixed air temperature can differ from point to point within the unit. In commercial units, the mixed air temperature is the average of three temperatures taken inside the mixed air space.)

The measurement of the air flow in residential units is aided by the fact that the calibrated flow grid is designed to fit into the air filter slot in these units. However, in some cases the fan was variable or multi speed and airflow could not be captured by a single measurement. Most units monitored in this work had single speed fans, so this was not a problem. In the future, more advanced units will be more likely to have variable speed fans that will require either logging the air flow directly or by means of an indicator such as the fan power or static pressure. A third subtlety in the measurements lies in the calculation of supply air enthalpy. Supply air is often at almost 100% humidity, especially if the evaporator coil is condensing water. Commonly used models of relative humidity sensors are not accurate in the range of about 90% to 100% humidity. Therefore, in this residential work, the supply air dry bulb temperature was tested; if it was below the saturation temperature of the return air absolute humidity, then supply enthalpy was assumed to be saturated. If the supply dry bulb temperature was above the saturation temperature then the supply enthalpy was estimated as a function of supply air dry bulb temperature and return air absolute humidity.

The thermal output defined above is then combined with the monitored total unit power to estimate the hourly efficiency EER, (output BTU/hr/ input Watt) as below:

EER hourly = hourly thermal output (BTU/hr) / electric input (Whr/hr)

The electric power of the unit is the power of the outdoor unit only; it does not include the supply fan power, which is added later. These monitoring measurements taken over the full monitoring period of one to two months are inputs to the analysis.

Three Steps of Analysis

A ground rule for this analysis is that it be based on the *in situ* cooling situation, where *in situ* includes all the cooling loads associated with the existing lifestyle patterns and as-found structure details including insulation, shading, and duct leakage as observed during the post-retrofit monitoring period. The analysis assumes that the building or lifestyle has not changed between the pre- and post-retrofit periods.

This need to preserve the *in situ* situation poses a complication because residential HVAC usage in a mild climate such as Southern California can be quite irregular, as it is dependent on occupancy patterns, ventilation strategies, building thermal mass, and, in more rare cases, evaporative cooling. Such a variable cooling usage situation is very difficult to model rigorously without extensive occupancy detail, and a simple “canned” average occupancy description often does not reflect the real-life situation. This analysis takes a middle course and posits a cooling model based on hourly outdoor temperatures that is constrained (calibrated) to report the same cumulative cooling energy as was monitored during the one to two month monitoring period, typically a significant portion of the cooling season. In this way, the effects of occupancy irregularities and lapses are incorporated in the long term cooling energy estimate. However, it needs to be noted that this analysis is restricted to estimates of the refrigeration-based cooling end use only and does not attempt to include cooling due to other viable cooling modes for this region, particularly night ventilation and evaporative cooling. Mechanical ventilation, absent compressor activity, is not included in this estimate.

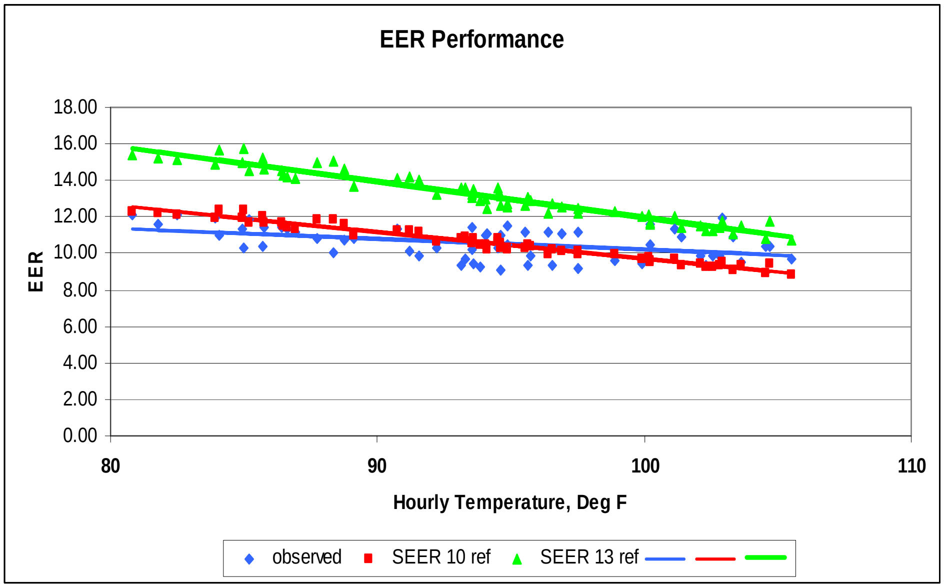
This analysis has been structured around three key empirical objectives. Each of these is briefly described here and developed more fully below.

Operating Efficiency Measurement

The first key empirical objective is directed at measuring the observed efficiency, EER, of the efficient installed unit as a function of hourly temperature. This work makes use of the empirical fact that for units of this genre the observed steady state EER will be an almost linear function of the outdoor dry bulb temperature. As a reference, this temperature vs. efficiency function is then compared to similar temperature vs. efficiency functions calculated for the SEER 10 and SEER 13 base case functions as derived from DEER values. The observed EER vs. temperature function for a given unit is compared to the EER vs. temperature functions derived from the monitoring of the base case samples and used to estimate performance of the ER and

ROB situations. These EER vs. temperature functions are reasonably orderly, and a comparison of these EER functions will appear as in Figure 1. This figure compares the EER function for the observed unit as well as similar functions derived for hypothetical DEER reference units. In this analysis, the DEER units are used as an upper bound on efficiency expectations, while the similar but lower efficiency EER curves for the ER and ROB base cases are used to express the efficiency that will ultimately be used in the calculation of the energy savings attributable to the observed unit.

Figure 1. EER vs. Temperature Functions



In Figure 1, the SEER 10 and SEER 13 EER vs. temperature functions were derived from generalized performance functions (bi quadratics) for HVAC units from the DEER database (DEER 2008 DX performance maps) that are used in eQuest models. These base case calculations are driven by the real observed hourly temperatures, outside air temperature (*T osa)* and entering wet bulb temperature *(T ewb*). The EER functions derived from DEER parameters generally show a slightly tighter scatter of points about the line than does the EER function derived from the monitored data.

Other research (such as the ADM study for SCE) has also monitored the operating EER. But this study, as is customary, normalized the empirical EER measurements to a standard outside air temperature of 95° F. The average normalized EER from this study compared well to the average EER at 95° F from the early replacement base case EER function. It is important to note here that a full EER vs. temperature function contains more information than a single point measurement. This extra content ultimately supports the estimate of annual energy use from these empirical measurements, which a single point estimate cannot do.

Most of the monitored sites region-wide are single stage units, but there are two stage units in the monitored sample and there are specific sub-regions where two stage units are a significant fraction of the total monitored units. Analysis of these units is more complicated and requires the use of some reasonable operating assumptions in order to develop an operating efficiency measurement.

The Cooling Energy Model

The second key empirical objective is directed at identifying the *in situ* site compressor-based cooling energy, including the effects of as-found occupancy and structural details. In this analysis, the final empirical result characterizes the site cooling energy for the compressor and condenser fan (not including the supply fan) as a linear function of hourly cooling energy versus hourly temperature as in Figure 2. This function will then be used along with the hourly long term temperatures from a long term typical year (TMY) to estimate the cooling energy for all hours of the year or cooling season.

Figure 2. Cooling Energy Functions

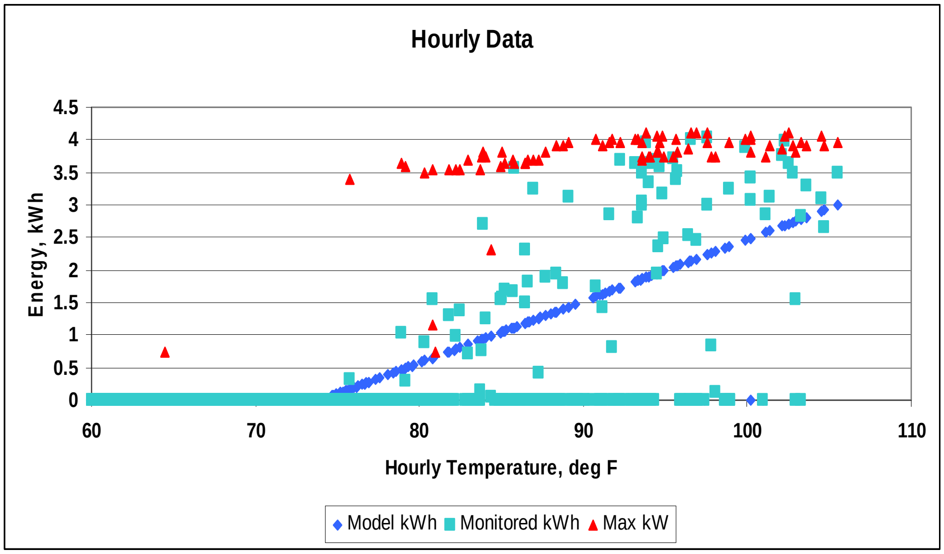
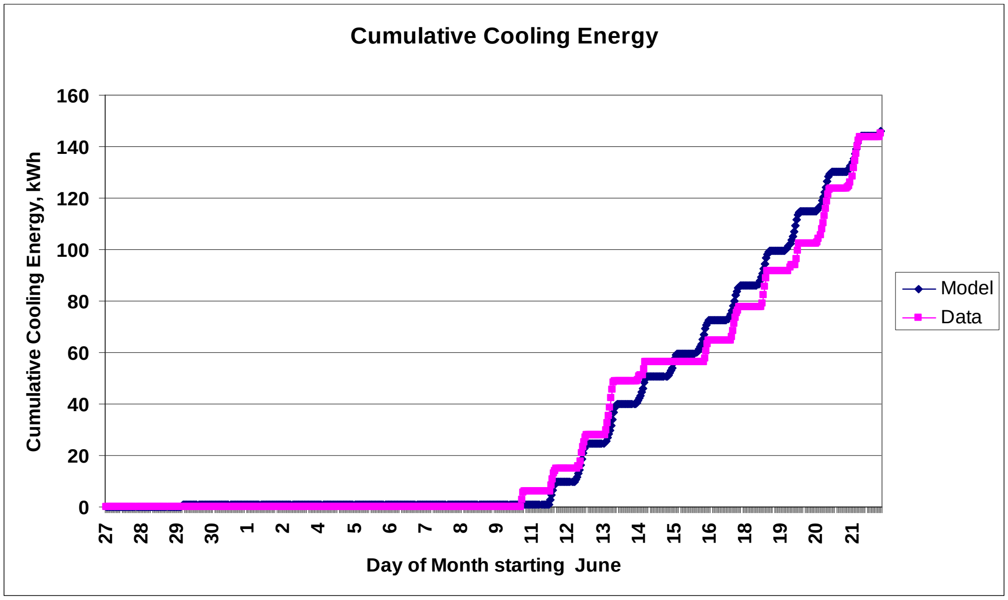


Figure 2 shows that a number of monitored kWh points are zero, even at high temperatures. In the early portion of the summer, cooling may not be triggered at all, even at high outdoor temperatures. This is because the thermal mass (or the occupant's tolerance of warmer weather) of the building was still in the range of 60-70°F, and had not yet responded to the warm days, thermally filtering out the brief warm events. After several warm days, the interior of the building had reached the range of 70-80°F, and cooling was then regularly triggered. This type of physical situation calls for the use of the temperature vs. kWh relationship that is conditional on interior or long term (3 day) running average temperature conditions which exceed a specified limit.

Figure 2 also shows the maximum power (max kW) observed in each cooling hour; this is indicative of site demand and is used in subsequent analysis to estimate hourly load factors and make the part load corrections required for use in the DEER analysis methodology.

Note also in Figure 2 that the modeled kWh vs. temperature function does not seem to bisect the cluster of points; it appears low. This low bias is necessary because at many high temperatures, mechanical cooling is not used at all for a variety of unknown occupancy reasons. The model kWh function has been constrained to reproduce the true sum of the cooling energy including the non-cooling intervals. Even though the cooling energy model only approximately fits the hourly data, it has been constrained to fit the longer term whole season data quite closely, as shown in Figure 3.

Figure 3. Cumulative Cooling Energy



A Full Normal Year 8,760 Cooling Estimate and Annual Total Cooling Energy

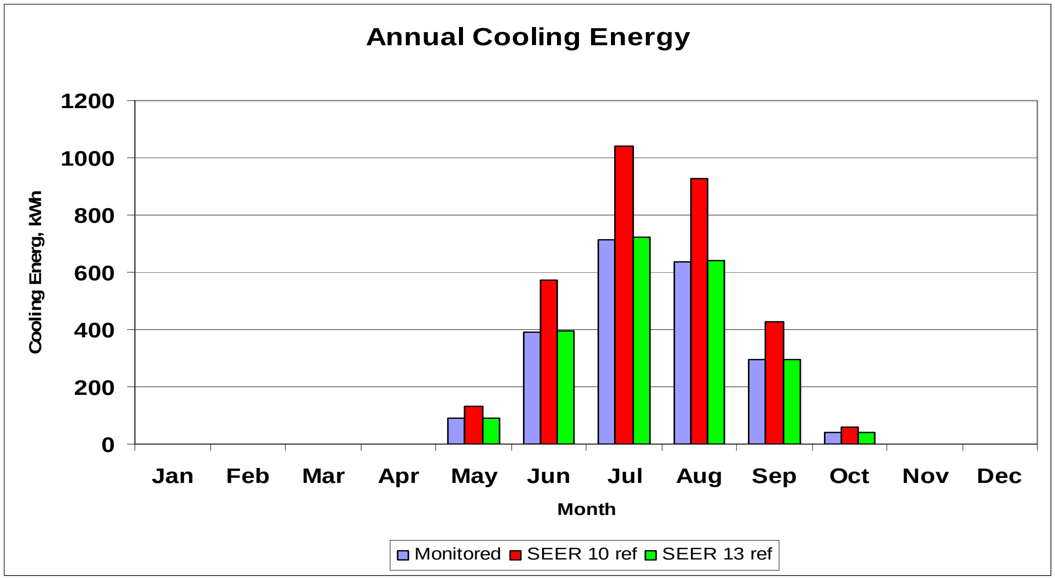
The empirical cooling efficiency and cooling energy model are used together as follows. First, the hourly cooling energy use for the full cooling season is derived using the kWh vs. temperature model and the appropriate zone normal temperatures. Second, the energy use for the base case situation is estimated by starting with the observed cooling energy for a particular hour at the monitored unit and proceeding to an estimate of the energy that would have been used in that hour by a hypothetical base case unit serving the same load under the same conditions. This is done by finding the EER of the monitored unit and the EER of the base case units at that same temperature and ratioing the energy use accordingly.

The total cooling energy is the sum of the outdoor unit energy as corrected for part load and the supply fan energy, as well as the modifications for part load factors on the DEER reference units. The sum of the total cooling energy for the 8,760 hour normalized year is the total annual cooling energy. The final output of the site analysis is an estimate of the annual cooling energy for the monitored unit and for the hypothetical SEER 10 and SEER 13 units operating under the same conditions that drive the monitored unit. Figure 4 shows an example comparison of the annual energy use by month for a site in Fresno, California.

This model for the monitored building and the SEER 10 and SEER 13 alternates may be used with the outdoor temperatures for a particular designated site, as provided by TMY hourly outdoor temperatures for that location. In this way, the performance of a building operating under the same conditions that prevailed inside the monitored building may be rendered for a variety of different locations, but essentially similar climate zones.

In Figure 4, the monthly cooling energy use has been aggregated into monthly estimates of cooling energy from an 8,760 estimate of hourly cooling energy use. Note in this example that the monitored unit appears to have the same energy use as the SEER 13 reference, as would be expected from the installation of a code-compliant unit. Note also that the SEER 10 reference shows greater cooling energy use due to the generally lower efficiency of the unit.

Figure 4. Comparison of Annual Cooling Energy



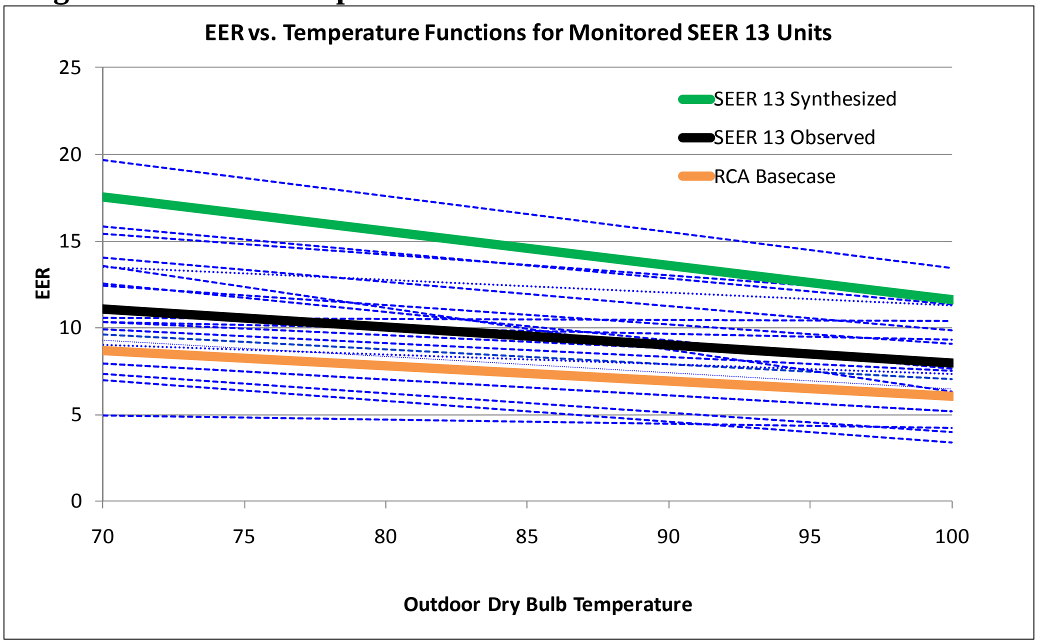
Summary of Results

Extensive detailed results from this work were used to develop savings estimates in the normalized form of kWh per yr per nominal ton, reported by utility and by climate zone. Results included peak demand savings using the definition of peak per the CA ALJ[i]. These results are found in the final report and appendices posted on the CPUC Energydataweb website. The most relevant of these results are discussed below.

The most striking result is shown in Figure 5. This figure shows EER vs. temperature results for the group of sites used to derive the SEER 13 base case for the ROB participants. The bold green line on this figure represents the EER vs. temperature function for a SEER13 unit as derived from the DEER information. This function reasonably represents the upper bound of the performance to be expected of an ideal SEER 13 unit. Note in this figure that the DEER upper performance bound is approached by only a few of the installed SEER 13 units, while most of the SEER 13 units apparently show a much lower efficiency.

In these low efficiency cases, the other monitoring information, such as supply air temperature and flow rate were re-examined to explain the apparent low performance. This low performance could not be reasonably explained by errors in the monitored data. This leaves the likelihood that the operating efficiency of current code SEER 13 units falls well below the ideal performance. At this point it is not known what site factors can explain this shortfall in SEER 13 performance. However, we have proposed laboratory work that will test the hypothesis that the low performance may be explained by low (or high) refrigerant charge or non-condensables in the refrigeration loop, since both these possibilities may be attributable to installation errors for residential units.

Figure 5. EER vs. Temperature Functions for Monitored SEER 13 Units



A second overall class of result from this work is that monitored cooling loads for mild climates such as San Diego and Los Angeles were much lower than estimated by the DEER methodology and by the various approaches used by the utilities. The monitored cooling loads for hot climates such as Palm Springs were reasonably consistent with the DEER methodology and utility estimates. Since the majority of the treated population was located in the mild zones, the lowered monitored cooling load in the mild zones led to realization rates for these programs that were lower than expected by the utilities or predicted by DEER modeling.

Conclusions and recommendations

This work has led to the following conclusions and recommendations.

1. The measurement of EER vs. temperature is an empirically achievable and diagnostically useful evaluation tool. This work shows that there are still important unexpected empirical findings that justify the time and expense of such monitoring. The situation regarding HVAC performance is not yet mature enough for an evaluation based entirely based on deemed or modeled values.
2. DEER and utility cooling load estimates for mild climate zones are too high and need to be re-calibrated.
3. Code level SEER 13 units perform at efficiencies lower than expected efficiency. This situation requires immediate follow-up and has been included in follow-up lab work we have proposed.
4. Air flow measurements are the key to this empirical approach. To accommodate future more sophisticated units with variable speed fans, the air flow measurement protocol needs to be improved by monitoring either fan power or static pressure correlated to site measured air flow rates.

5. The sample sizes for this work proved to be too small to achieve the intended 90/10 precision. This was due to attrition of the monitoring sample from either overt monitoring problems or monitoring equipment installed too late to capture a sufficient fraction of the annual cooling load. It is very important to plan a monitoring campaign for cooling equipment well in advance of the required summer monitoring season.

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[i] The CA Administrative Law Judge (ALJ) issued decision R.06-06-063 on June 29, 2006 establishing the definition for peak as it applied to the evaluation effort. The order established peak as the average grid-level impact for a measure between 2 p.m. and 5 p.m. during the three consecutive weekday periods containing the weekday with the hottest temperature of the year. DEER identifies these three contiguous peak kW days for each of the 16 California climate zones, based on the weather data sets developed for the California Title 24 Building Energy Efficiency Standards.