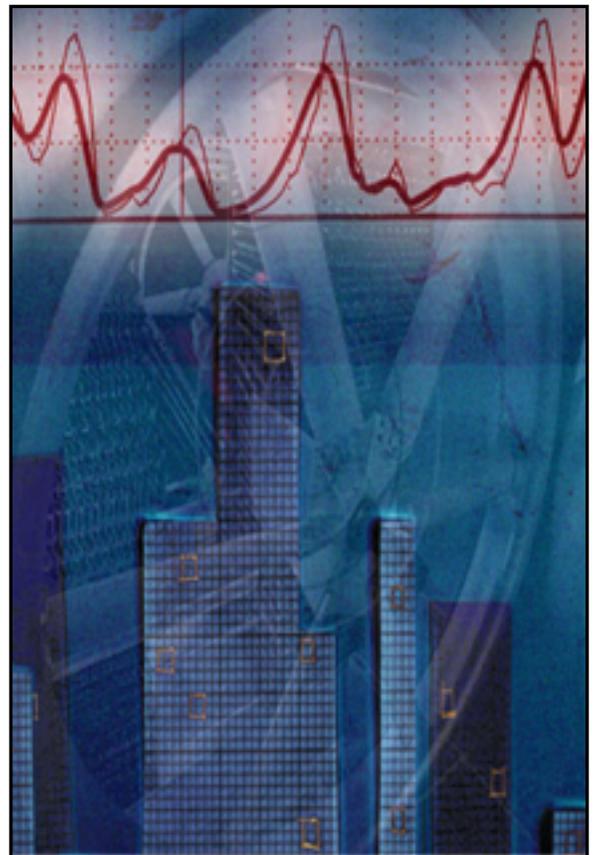

EER & SEER AS PREDICTORS OF SEASONAL COOLING PERFORMANCE

SUMMARY OF RESEARCH

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1.0 Introduction

The air conditioning industry in North America has long relied on the Energy Efficiency Ratio (EER) and the Seasonal Energy Efficiency Ratio (SEER) as indicators of cooling HVAC equipment efficiency and performance. EER is “a ratio calculated by dividing the cooling capacity in Btu/h by the power input in Watts at any given set of rating conditions, expressed in Btu/h/W” (ARI, 1984). Currently, all direct expansion (DX) air conditioners are rated using EER, a rating standardized by the Air-Conditioning and Refrigeration Institute (ARI), which reports steady-state efficiency at 95°F outdoor and 80°F dry-bulb, 67°F wet-bulb indoor temperatures. Smaller residential-sized air-conditioners, i.e., < 65,000 Btu/hr, are rated using SEER, a rating developed by the U.S. Department of Energy (DOE) in 1977 (Kelly and Parken, 1978) and first adopted by DOE in 1979 (DOE 1979). SEER is “the total cooling of a central air conditioner in Btu’s during its normal usage period for cooling ... divided by the total electric energy input in watt-hours during the same period...” (ARI 1984). The SEER test procedure is very similar to that used for EER, i.e., a simple short-term steady-state laboratory test. By using a milder outdoor temperature (82°F rather than 95°F) considered to represent a national average cooling condition and by including cycling losses, the SEER rating is intended to better indicate average seasonal performance, or in other words, a season-long "average" EER. Details of the SEER testing and rating process are provided in Appendix A.

Since its inception over 20 years ago, SEER has become the codified standard by which the efficiency of small air-cooled electric HVAC cooling systems is compared. In California, Title 20 and Title 24 appliance and building energy standards have long mandated air conditioner efficiency levels using SEER. Consumers are also typically guided to make energy-wise purchases based on these ratings. For example, “consumers can compare the efficiency of central air conditioners and heat pumps (in the cooling cycle) using the SEER. The higher the SEER, the more efficient the system...” (California Energy Commission Web site).

Driven largely by suspicions that SEER may be an unreliable predictor of peak demand savings, in recent years the California utilities’ state-wide efficiency programs have abandoned SEER in favor of EER as an indicator of both energy and demand benefit (for example, see the state-wide *Savings By Design* incentive program requirements at www.savingsbydesign.com/system.htm). Others have recently questioned the efficacy of SEER as an indicator of cooling efficiency (Kavanaugh, 2002). Accordingly, this study examines the efficacy of using SEER when making cooling system efficiency decisions and recommendations.

1.2 Organization of this Document

This document provides a summary of only the most important portions of a longer report by the same name. Consequently, this summary is intended to be brief and makes liberal use of bulleted descriptions. Key research questions are presented in bold font in each section, as are the most essential portions of the answer to the question. The contents are organized as follows:

- An introduction and description of the questions that motivated and guided this study;
- A description of the key assumptions of the SEER rating process ;
- A description of the analysis methodology used in the study;
- Findings regarding the validity of the key assumptions of the SEER rating procedure;

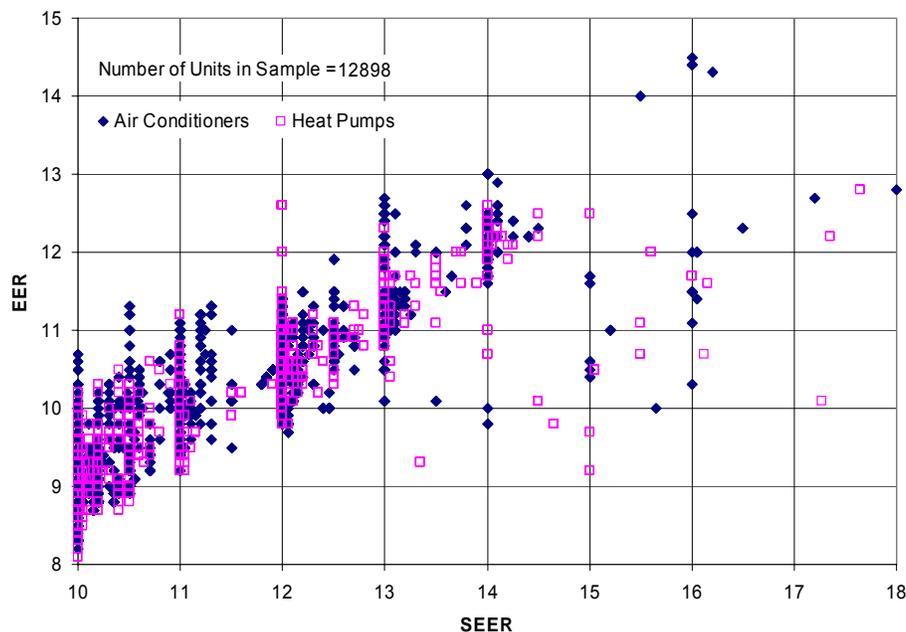
- Findings that address the questions that guided the research;
- A summary of findings and “next steps”

The study revealed VERY different findings for residential versus non-residential applications. Accordingly, the findings are presented separately, first the residential findings, then the non-residential findings. The residential findings are presented in much more detail than are the non-residential findings. For more detailed information, the interested reader is referred to the full report, especially regarding the non-residential findings.

1.3 Objective of the Study

The justification for this study originated with the scatter observed in Figure 1 below. The data in Figure 1 are taken from the California Energy Commission (CEC) data base of unitary HVAC equipment (approximately 13,000 HVAC systems). In Figure 1, the SEER rating (tested at 82°F) for HVAC systems are plotted against the EER (tested at 95°F) rating for the same equipment. The data in Figure 1 indicate that HVAC systems with similar efficiency at 82°F (for example, SEER 12) show a large degree of variation in their efficiency at 95°F (EER 9.5 to 11.5+). Given the large amount of scatter in Figure 1, a reasonable question is: how could cooling systems with the same SEER, but with very different EER's (Figure 1), have the same season-long performance? The scatter in this data clearly indicates that many cooling systems that perform similarly at outdoor temperatures of 82°F (i.e., have the same SEER rating) may perform very differently at outdoor temperatures other than 82°F (i.e., not just at 95°F); hence, the reliability of SEER as an indicator of either seasonal energy efficiency or peak demand may be limited. Assessing the sign and magnitude of these limitations across typical California applications, both residential and non-residential, and across all California climates is the objective of this study.

Figure 1 Performance Characteristics of SEER-rated Cooling Systems
Rated SEER (at 82°F) versus Rated EER (at 95°F)



1.4 Questions that Guided the Research

This analysis seeks to answer the following specific questions regarding the efficacy of using SEER to make efficiency investment decisions and recommendations:

- 1) *How effective is SEER as a predictor of expected annual cooling energy use?*
- 2) *How effective is SEER in estimating cooling energy savings?*
For example, based only on the difference in magnitude of SEER, upgrading from SEER 10 to SEER 12 represents a 20% improvement in SEER ((1-[12/10]), and suggests a 17% reduction in annual cooling energy use (1-[10/12]). All other things being equal, i.e., controlling for climate and user differences, will a 17% savings in annual cooling energy be realized?
- 3) *How effective is SEER in estimating the relative seasonal cooling efficiency of different cooling systems, i.e., rank ordering seasonal performance?*
Like the EPA gas mileage label, “your mileage may vary”, actual seasonal efficiency may vary due to user effects such as thermostat setpoint. Notwithstanding this, can SEER be used to compare the *relative* cooling efficiency of air conditioners? For example, for a specific house and climate zone, will a SEER 11 system reliably use less annual cooling energy than a SEER 10 system?
- 4) *How effective is SEER as a predictor of expected cooling peak demand and demand savings?*
This question has become all the more important since ARI decided in November of 2002 not to include a rated EER value for SEER-rated units in its directory of certified equipment.

2.0 Background: Key Assumptions in the SEER Rating Methodology

How can air-cooled cooling systems with the same SEER (same efficiency at 82°F), but with very different efficiencies at other temperatures (e.g., EER at 95°F, see Figure 1), actually have the same season-long cooling efficiency? Further, **how can an estimate of season-long cooling efficiency that is valid across varied climates and operating conditions, be determined using only one (or at most a few) steady-state test(s) conducted in a controlled laboratory setting?** Necessarily, the SEER rating process is based on several key assumptions.

2.1 How the SEER rating process accommodates the “scatter” in Figure 1.

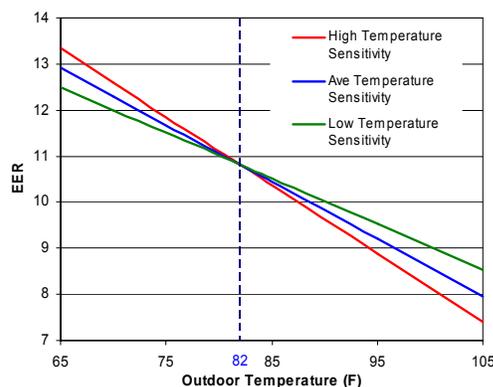
The following key assumptions are implicit in the SEER rating process.

- 1) Cooling energy use is entirely determined by the indoor-to-outdoor temperature difference.
- 2) The sensitivity of cooling system efficiency to outdoor temperature is linear.
- 3) A steady-state test conducted at the *mid-load* temperature (i.e., the outdoor temperature that separates annual cooling loads into two equal halves) will indicate the annual average energy efficiency of cooling systems (despite differing efficiency at other outdoor temperatures).

An example: imagine two cooling systems with equal SEER (i.e., equal efficiency measured at 82°F) but differing sensitivity to outdoor temperature (i.e., one system has higher EER than the other, as in Figure 1).

- The system with higher temperature sensitivity will be less efficient at hotter outdoor temperatures than the other system (e.g., in Figure 1, the system with lower EER).
- IF sensitivity to temperatures is even approximately linear, then the system with high sensitivity (lower EER in Figure 1) will also tend to be more efficient at lower temperatures than the other system (i.e., higher EER when measured at any temperature lower than 82°F, see Figure 2).
- While energy use measured at any temperature other than 82°F will differ between the two systems, over an entire cooling season, these differences in efficiency will balance out and the two systems will have the same season-long energy use, IF sensitivity to temperatures is perfectly linear and IF 82°F (the SEER outdoor test temperature) represents the *mid-load* temperature (i.e., the outdoor temperature above and below which occurs exactly half of the annual cooling coil load).

Figure 2
Cooling System Performance Assumptions Implicit in the SEER Rating Process
Efficiency (EER) Sensitivity to Outdoor Temperature



In summary,

IF cooling efficiency sensitivity to outdoor temperatures is perfectly linear, AND

IF a cooling system's efficiency is measured at a mid-load temperature that is representative of varied climates and operating conditions, AND

IF cooling energy use is entirely determined by the indoor-to-outdoor temperature difference,

THEN

SEER should be able to provide a prediction of season-long cooling efficiency that is valid across varied climates and operating conditions. Further, cooling systems with identical SEER ratings (same efficiency at 82°F), but with different efficiencies at other temperatures (e.g., EER at 95°F) as illustrated in Figure 1, will have the same season-long cooling efficiency.

2.2 The origin of 82°F in the SEER rating process

Probably the most widely known assumption implicit in the SEER rating procedure is the use of a national average standard seasonal cooling coil load profile with median of 82°F. The assumptions that were made in its selection are not as widely understood. They are as follows.

- The distribution of outdoor temperatures that coincide with cooling is as illustrated in Figure 3a (median value of approximately 76°F).
- The building thermal characteristics (e.g., overall shell U-value, solar gains, internal loads, thermostat cooling setpoint, etc.) yield a 65°F balance point for the building (i.e., no cooling required below 65°F as illustrated in Figure 3b).
- All cooling coil load is a linear function of outdoor temperature only (Figure 3b).
- The preceding three assumptions result in a seasonal average coil load with distribution as illustrated in Figure 3c with median of 82°F, i.e., a *mid-load* temperature. In other words, in Figure 3c, exactly half of the annual cooling coil load coincides with outdoor temperatures above 82°F, the other half coincides with temperatures below 82°F.

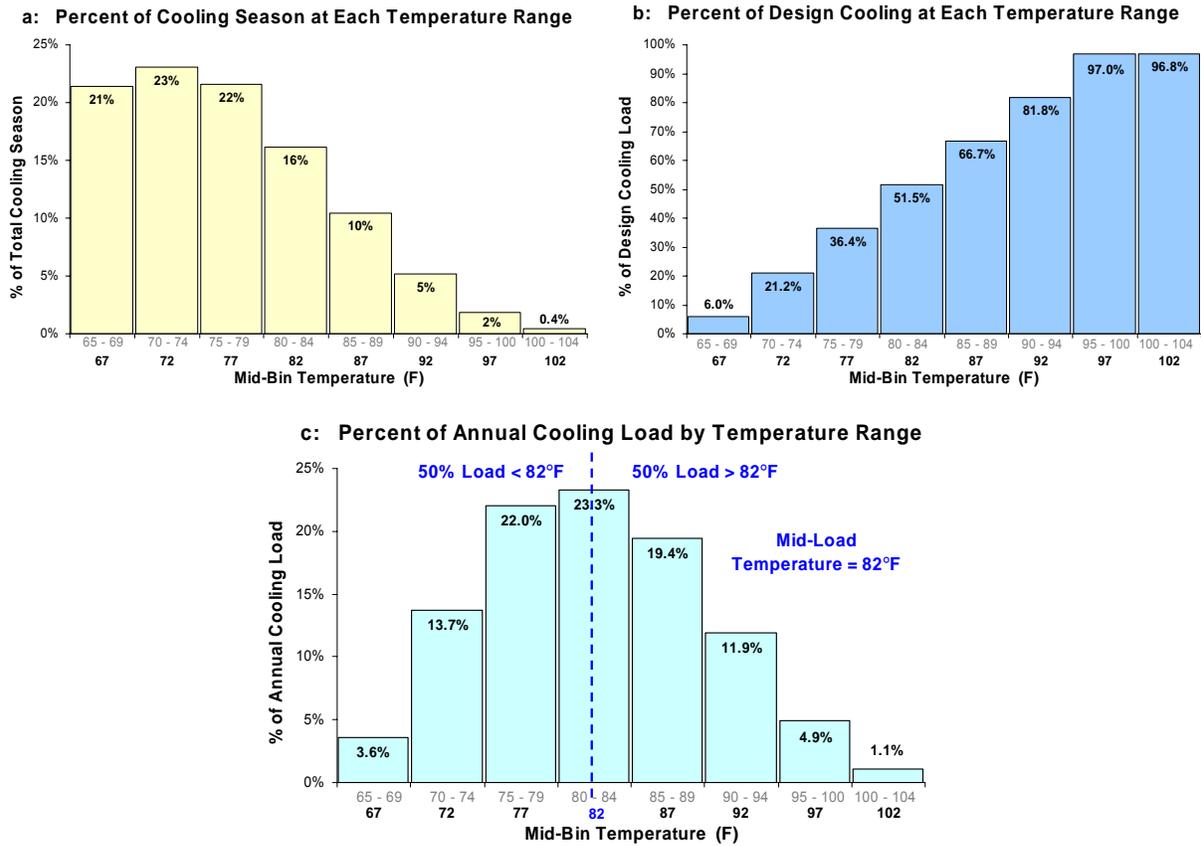
These assumptions led to the selection of 82°F as the outdoor temperature for the SEER rating.

2.3 Fan energy in the SEER rating process

Fan energy is included in the total cooling system energy considered in the SEER rating process. Since indoor (evaporator) and outdoor (condenser) fan energy are included in the SEER rating, the assumption that total cooling energy is a linear function of outdoor temperature requires at least two further assumptions regarding the behavior of indoor and outdoor fans. The role of indoor fan energy turns out to be very important in non-residential applications due to code-mandated ventilation requirements.

- Energy from both fans is assumed to be a relatively small portion of the total energy requirement.
- Both fans are assumed to cycle with the compressor, thus fan energy is proportional to compressor energy.

**Figure 3: Key Assumptions Implicit in the SEER Rating Procedure
Derivation of the 82°F “Mid-Load” Temperature**



Of course, the informed reader will recognize that none of the assumptions described above and which are implicit in the SEER rating process are universally valid. This research examines the validity and consequence of these assumptions for typical California residential and non-residential buildings across all sixteen California climate zones and attempts to estimate both the sign and magnitude of any bias in SEER for common California applications.

3.0 Analysis Methodology: Understanding What Impacts SEER

3.1 Factors that effect SEER efficacy

An analysis methodology was selected to help understand the factors that affect SEER and its efficacy when used to make cooling equipment efficiency selection decisions. Broadly, these factors are:

- Climate characteristics
- Cooling load characteristics (due to building characteristics)
- Individual HVAC system characteristics

Climate characteristics

California climates vary from that assumed by the SEER rating methodology. i.e., the cooling season median temperature may not be 82°F.

- Initial analysis was conducted using five “indicator” climate zones: Oakland (CZ03), Long Beach (CZ06), San Diego (CZ07), Sacramento (CZ12), and Palm Springs (CZ15). These were selected to capture the typical range of California cooling climates and to include the area of population concentration.
- Final analysis was conducted using all climate zones except CZ01 (north coast) since no cooling is required (when used, this tended to unreasonably skew the results).

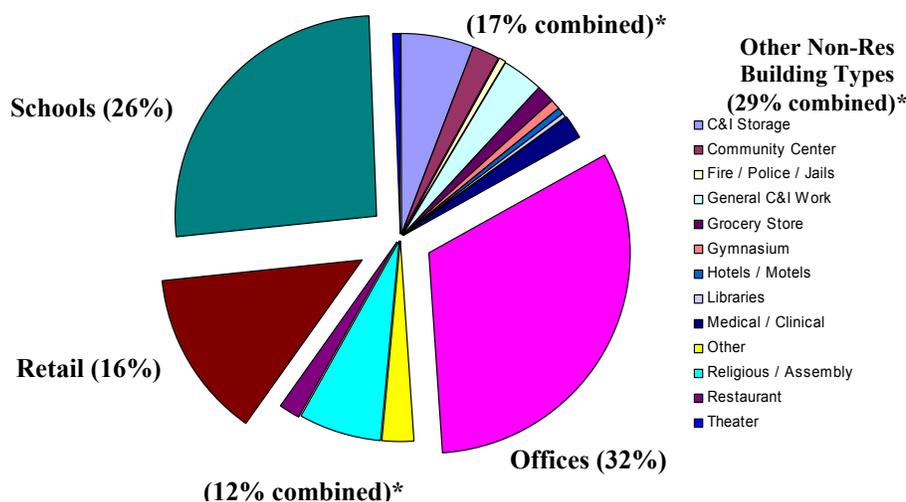
Cooling load characteristics (building load characteristics)

Several building thermal characteristics will help determine the *mid-load* temperature, including the following.

- Zone balance point — The balance point of a building is the outdoor temperature at which the losses through the building envelope are balanced by solar and internal gains. Below this outdoor temperature the building needs heating and above this temperature the building needs cooling. The balance point of the areas of a building served by SEER-rated HVAC systems may differ significantly from 65°F assumed by SEER due to building characteristics such as cooling thermostat setpoint, solar gain (i.e., zone glass area and zone orientation), internal load, zone shell overall U-value (including whether the zone is perimeter or core), and whether natural ventilation or economizer cycles are employed.
- Zone operating schedule — Does the zone served by the SEER-rated HVAC system operate overnight or only during the day and do building and system features such as natural ventilation or economizer cycles cause the HVAC equipment to operate only during the hours of warmest outdoor temperature?
- Linearity of the relationship between cooling coil load and outdoor temperature — Is the relationship between cooling coil load and outdoor temperature linear as assumed by the SEER rating methodology? Factors that cause the load not to be strictly linear include building envelope mass and internal mass, mass of the HVAC distribution system, long wave radiant losses, and sol-air effects (the effect of sunlight raising the outdoor surface temperatures of dark surfaces well above outdoor temperature).

These thermal characteristics will tend to vary by building type. To determine which building types should be included in the analysis, recent California new construction building surveys were examined to determine where the majority of the SEER-rated equipment was installed (*2000 Residential New Construction Market Share Tracking (RMST) Database* and the *1999 California Non-Residential New Construction Characteristics (CNRNCC) Database*). Figure 4 illustrates the distribution of SEER-rated cooling systems among non-residential building types.

Figure 4 Percent of Total Installed Tons of SEER-Rated A/C Systems in California Non-Residential Buildings



Based on the results illustrated in Figure 4, the building types selected for inclusion in this analysis were:

- Single-family Residential
- Small office
- Small Retail
- Conventional School Classrooms
- Portable School Classrooms

Variation in seasonal cooling load profiles will also be caused by variations in thermally significant building characteristics. Building prototypes included as many as twenty variable building features. These were used to describe and vary the thermal characteristics and operation of each building prototype. Building design and operations features were identified for each building type that was considered important in varying the cooling load “shape”, i.e., the relationship between cooling load and outdoor temperature (see for example, Figure 3c). These include detailed descriptions of the building components (walls, windows, building orientation, shading devices, floor area, number of floors, etc.) and building operating conditions (occupancy levels, thermostat settings, equipment use, lighting, and schedules that describe how these vary over the day). Lists of building characteristics that impact the cooling load shape are provided in Table 1 for the single-family residential prototype, and Table 2 for the small office prototype. The building component and operational details are obtained from new construction building surveys conducted in California (*2000 Residential New Construction Market Share Tracking (RMST) Database* and the *1999 California Non-Residential New Construction Characteristics (CNRNCC) Database*). Using these surveys, median, minimum, and maximum values of the components and operational features of the building prototypes were determined.

Table 1 Single-Family Residential Prototype Cooling Load-Related Characteristics

Total Floor Area	Conditioned floor area
Number of Stories	Typically a fraction that includes 1 & 2 stories
Aspect Ratio	Orientation of long axis varies
Occupancy	Includes number and schedule of use
Internal Gains	Net loads to the space
Glass Area (Fraction)	As a fraction of total wall area
Glass U-factor	NFRC U-factor
Glass SHGC	NFRC solar heat gain coefficient
Shading Level	Shading by overhang
Ceiling Type	Cathedral or attic
Roof Insulation	Roof overall U-value
Wall Construction Type	Construction and U-values varies
Floor Type	Crawlspace or Slab
Floor Insulation	U-value of floor or slab loss factor
Infiltration	Infiltration rate in air-changes/hour
Natural Ventilation	Varied by indoor temperature and ventilation rate
Cooling Thermostat	Consistent with natural ventilation
Cooling T-stat Setup	Consistent with occupancy schedules
Duct Loss (fraction)	Fraction of return and supply cfm lost to outside
Duct R-Value	Duct insulation value

Table 2 Small Office Building Prototype Cooling Load-Related Characteristics

Total Floor Area	Conditioned floor area
Internal Shade Prob	Based on solar lighting levels
Perimeter Depth	Perimeter office depth
Occupancy	Given as floor area per person
Schedule	Total hours of occupancy per day
Roof Insulation	Built-up roof insulation
Exterior Wall Insulation	U-value of wall insulation
Wall Const Type	Heavy or light construction
Lighting Power Density	Watts/sq. ft.
Plug Power Density	Watts/sq. ft.
Glass U-factor	NFRC U-factor
Glass SHGC	NFRC solar heat gain coefficient
Glass Overhang	Shading by overhang
Economizer	Default is none
Glass Area (Fraction)	As a fraction of total wall area
Cooling Thermostat SP	Consistent with occupancy schedules
Aspect Ratio	Orientation of long axis varies

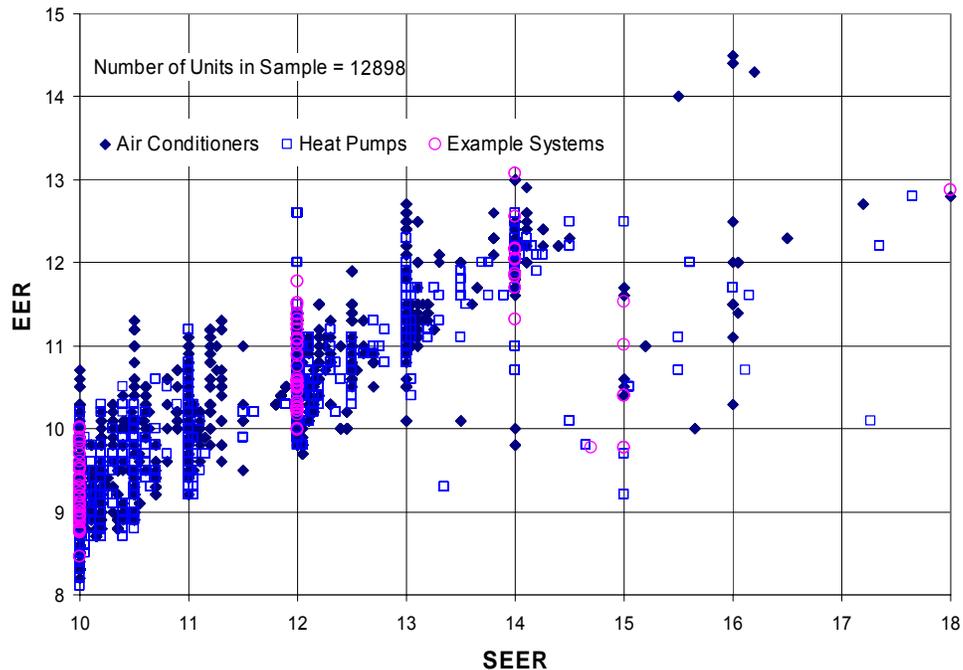
HVAC system characteristics

Individual differences amongst equivalent SEER-rated HVAC systems, as illustrated in Figure 1, can lead to variations in annual cooling energy and peak demand among identically SEER rated equipment. Approximately ninety HVAC systems were selected from a data base of over 570 to reflect the range of currently available systems. The selection process examined equipment sensitivity to the effects listed below. Actual systems were selected that closely represented high, median, or low sensitivity to each.

- Sensitivity to outdoor temperature
- Sensitivity to compressor cycling effects
- Sensitivity to coil entering conditions (indoor dry-bulb and wet-bulb temperature, the SEER rating methodology assumes a constant coil entering condition of 80°F dry-bulb and 67°F wet-bulb)

Figure 5 contains the same data as Figure 1 but also includes the ninety representative HVAC systems selected for this analysis. As can be seen in Figure 5, the selection process successfully reflects the range of systems originally illustrated in Figure 1.

Figure 5
Performance Characteristics of SEER-rated Cooling Systems Selected for this Analysis
Rated SEER (at 82°F) versus Rated EER (at 95°F)



3.2 Simulation Analysis Key Assumptions

DOE-2.2 was used to conduct the simulation analysis for this research. Several key assumptions underlying this analysis approach are:

- Substantial prior experience with DOE-2 has convinced the California energy efficiency industry that DOE-2 is fully capable of capturing the interaction of climatic and building thermodynamics, and replicating system performance when detailed manufacturers' data is used.
- For this research, all simulations were run using manufacturers' extended ratings data to fully capture individual system performance, i.e., each run used one or more "actual" cooling systems available in the market. No DOE-2 default performance characteristics were used.
- Since annual cooling energy use will vary widely depending on climate zone, building characteristics, and system characteristics, comparing rated SEER-predicted energy use against DOE-2 detailed simulation results must be normalized if results from different climates, building configurations, or systems are to be compared. Toward this end:
 - This study determined to compare effects across various climates, buildings, and systems by comparing rated SEER with "DOE-2 simulated SEER" rather than comparing projected annual cooling energy use.
 - "DOE-2 Simulated SEER" is calculated using the results of detailed DOE-2 simulations, i.e., the ratio of simulated annual cooling coil load to the simulated cooling energy required to meet the load (including indoor fan energy).
 - For the purposes of this study, DOE-2 simulated SEER (using statistically valid climate and building characteristics and manufactures' detailed cooling performance data) provides a valid reference indicator of actual annual cooling energy efficiency.
- If agreement between rated SEER and DOE-2 simulated SEER were perfect, a graph plotting one against the other would show all points falling on a straight line having a slope of 1.0. Any scatter in such a graph, i.e., the vertical distance a point falls above or below the slope 1.0 line, provides a convenient indication of both the sign and magnitude of disagreement between rated and simulated SEER. Taking DOE-2-simulated SEER as the standard, the degree of scatter will indicate the amount of error in using rated SEER to anticipate annual cooling savings.

3.3 Simulation Analysis Process

Simulation analysis strategies were selected to estimate the sign and magnitude of bias in existing SEER ratings that compromise its efficacy when used to make cooling equipment efficiency selection decisions. This analysis attempts to partition the estimates of SEER bias into the following three effects:

- Climate effects — do differences between California climates and the national average climate assumed by the SEER rating process compromise the efficacy of SEER in predicting annual cooling energy use in California and if so what is the sign and magnitude of that effect?
- Effects of cooling load (i.e., building) characteristics — how valid is the SEER-assumed 82°F *mid-load* temperature for typical California buildings in California climates? The mid-load temperature is a function of both the climate and building characteristics (e.g., via the balance point). What is the sign and magnitude of any effect building type and the typical range of variation in individual building characteristics may have on SEER efficacy?
- Effects of HVAC system sensitivity to operating conditions — how much variation in actual annual cooling energy performance results from individual differences between systems with the same SEER rating (i.e., the scatter in Figure 1)?

For convenience, these will be referred subsequently as “climate effects”, “building effects”, and “system effects”. The analysis process used to isolate the effect of each is described below.

Determining the average climate effect — To determine the average effect of California climate variation from the national average climate assumed in the development of the SEER rating, simulate median building prototypes and median system characteristics over the subset of indicator climate zones, i.e., Oakland (CZ03), Long Beach (CZ06), San Diego (CZ07), Sacramento (CZ12), and Palm Springs (CZ15). Compare simulated SEER (determined by detailed simulation) to rated SEER to identify the sensitivity of rated SEER to California climates.

Determining the average effect of building characteristics on SEER — To determine the average effect of building characteristics on SEER, modify building characteristics (approximately twenty for each prototype) in a sequential manner to determine the unique combination of characteristics that yield the highest and lowest simulated SEER values for each climate zone (i.e., differs by climate; use only the indicator climate zones). Compare simulated SEER to rated SEER to identify the sensitivity of rated SEER to the typical variation in California buildings. Use these results to estimate the expected uncertainty in SEER based on building characteristics.

Determining the average effect of HVAC system characteristics on SEER — To determine the average effect of variation in individual HVAC system characteristics on SEER, simulate the building prototypes that produce the median SEER values resulting from the previous step using the full set of example cooling systems having minimum, maximum, and median sensitivity to outdoor temperature and cycling effects. Use these results to estimate the expected uncertainty in actual SEER due to the typical variation in individual cooling system performance characteristics for systems with the same SEER rating (i.e., the scatter in Figure 1).

4.0 Findings regarding key assumptions of the SEER rating procedure

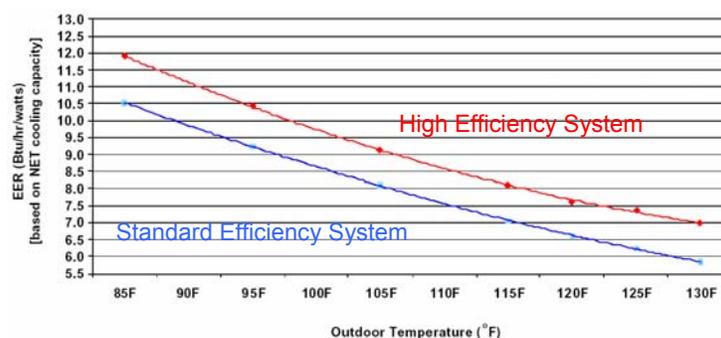
Several assumptions implicit in the SEER rating process, described previously in Section 2, are not realistic for California buildings and climates. This section examines the validity of these assumptions for typical California residential buildings across all California climate zones.

4.1 Cooling efficiency is linearly in outdoor temperature

How valid is the assumption that cooling efficiency sensitivity to outdoor temperature is linear? See Figure 6.

For many cooling systems, the sensitivity of cooling efficiency to outdoor temperature tends to be linear (Figure 2), however, this is not always the case (Figure 6).

Figure 6 System Efficiency (EER) as a function of outdoor temperature



Source: Performance Evaluation of Typical Five Ton Roof Top Air Conditioner Units Under High Ambient Temperatures, Southern California Edison, 2003

4.2 U.S. average SEER climate

How similar are California climates to the U.S. average SEER climate? See Figure 7.

Figure 7 (page 17) compares the outdoor air temperature distribution assumed by the SEER rating methodology (see Figure 3a) with the distribution of outdoor temperatures for each of the sixteen California climate zones. Figure 7 also includes a comparison to the California average distribution (i.e., average of all sixteen climate zones) and the average distribution from the major California urban centers, i.e., climate zones CZ 3 (Oakland), CZ 6 (Long Beach), CZ 7 (San Diego), and CZ12 (Sacramento). In Figure 7, the dark blue vertical bars represent the relative frequency distribution of outdoor temperatures in California climates. The orange curve represents the same relative frequency for outdoor temperatures assumed by the SEER rating procedure (i.e., same as Figure 3a). While most of the vertical axes in Figure 7 use a constant scale, those whose vertical scales differ are shown in color (i.e., orange).

The results in Figure 7 suggest that climate zones 10 and 12 are closest to the distribution of outdoor temperatures assumed in the development of SEER. **In general, most of the California climate zones appear to be cooler than the SEER assumed national average.** Only climate zones 13, 14, and 15 (Palm Springs) appear to be warmer than the SEER national average.

4.3 SEER 82°F *mid-load* temperature

How valid is the SEER 82°F *mid-load* temperature and associated distribution of annual cooling coil loads for typical single-family homes in California climates? See Figure 8.

The SEER rating procedure assumes that 82°F represents the *mid-load* temperature for the average U.S. climate. Figure 8 compares the relative frequency distribution of cooling loads for a typical single family residence in California (as determined by DOE-2 simulation using the median single-family residential prototype) with the national average SEER-assumed distribution, for each of the sixteen California climate zones. Graph layout and color conventions in Figure 8 are the same as was explained for Figure 7. For each case in Figure 8, the mid-load temperature is indicated (contrast these temperatures with 82°F), as is the percentage of annual cooling hours above and below 82°F (the SEER rating procedure assumes that 50% of the cooling load falls above and below 82°F).

The results in Figure 8 suggest that climate zone 9 (Pasadena) is closest to the distribution of outdoor temperatures assumed in the development of SEER with cooling load distributions shifted toward the cooler range for about half of the climate zones and shifted toward the warmer range for the other half. Given the “symmetry” of the results in Figure 8, perhaps it is not surprising that the California average distribution reports to be relatively similar to the SEER national average (80°F mid-load temperature). Note that these results suggest that **for the median house, California urban residential applications would be better served with a SEER rating procedure that assumes 76°F, rather than 82°F.**

4.4 Linearity of cooling load with outdoor temperature

Is the linear relationship between cooling load and outdoor temperature assumed by SEER rating process valid for typical (median) California single-family houses? See Figure 9.

Figure 3b above illustrated the simple linear relationship between outdoor temperature and load implicit in the SEER rating procedure. Figure 9 illustrates the role various climate factors, as well as building design features, have on cooling coil load. The data in Figure 9 are a full year of simulated hourly cooling coil loads plotted against the outdoor temperature at which each hourly load occurred. They were generated using the DOE-2 model of the median single-family one-story house used in Figure 8. Climate zone 9 was selected for all cases illustrated in Figure 9 since it most closely matched the mid-load temperature assumptions implicit in SEER.

Figure 9a illustrates a simulation case that demonstrates a significantly linear relationship between hourly cooling coil load and outdoor temperature, as is assumed in the SEER methodology. The slope of the line in Figure 9a represents the overall U-value for the house (U_0). The point at which the line meets the X-axis (zero cooling coil load) represents the balance point of the house (in Figure 9a, in the absence of internal gains and solar gains, the cooling balance point is the same as the thermostat cooling setpoint, or 78°F).

Obtaining the straight line relationship between hourly cooling coil load and outdoor temperature illustrated in Figure 9a required numerous simplifications to the DOE-2 prototype and simulation procedure. Each of the cases included in Figure 9, other than the first one, i.e., Figure 9b through 9L, represent separate annual simulation results in which one important climate or house design

Figure 7 Distribution of Cooling Season Outdoor Temperature California Climate Zones vs. SEER rating assumption

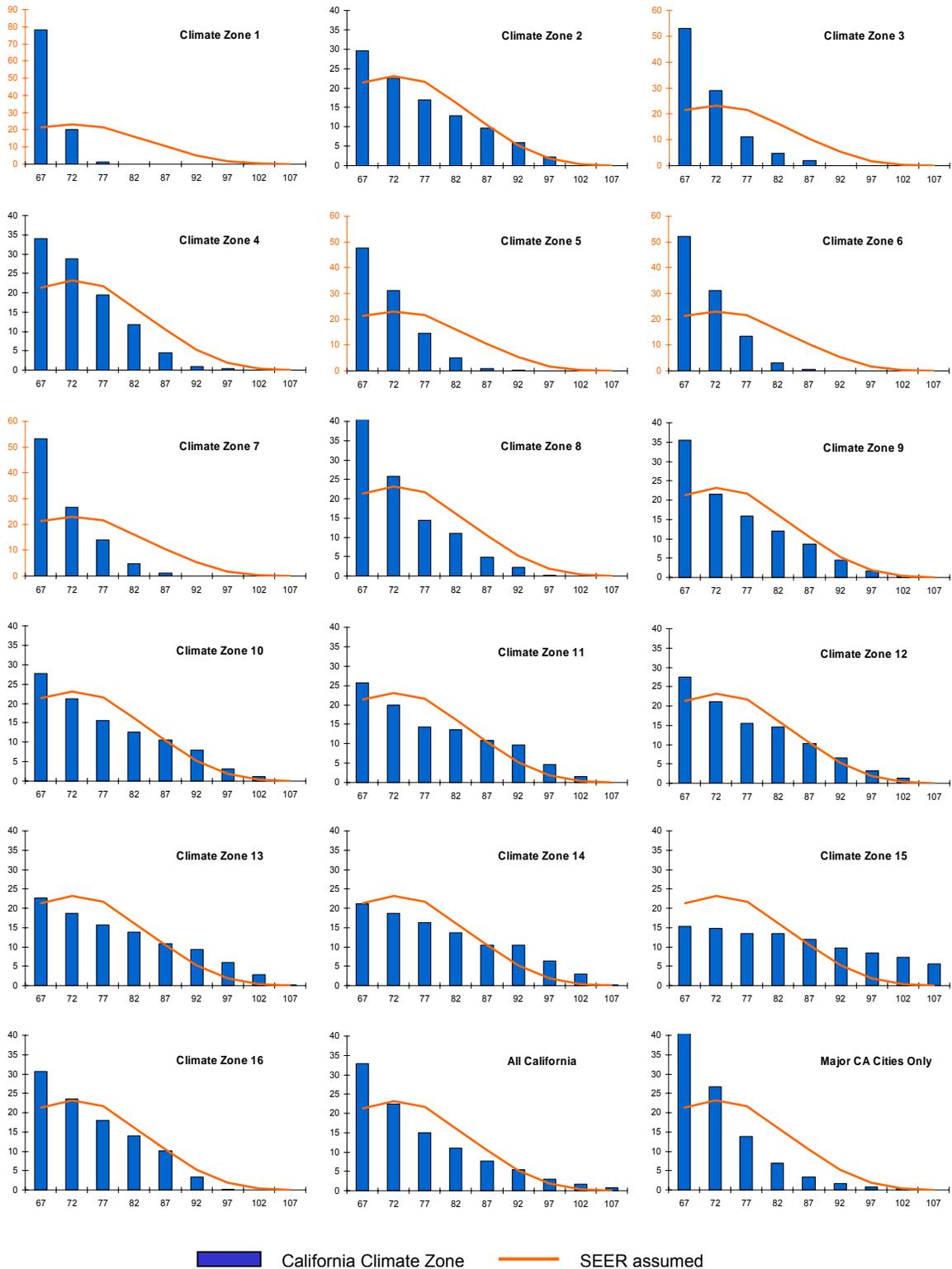
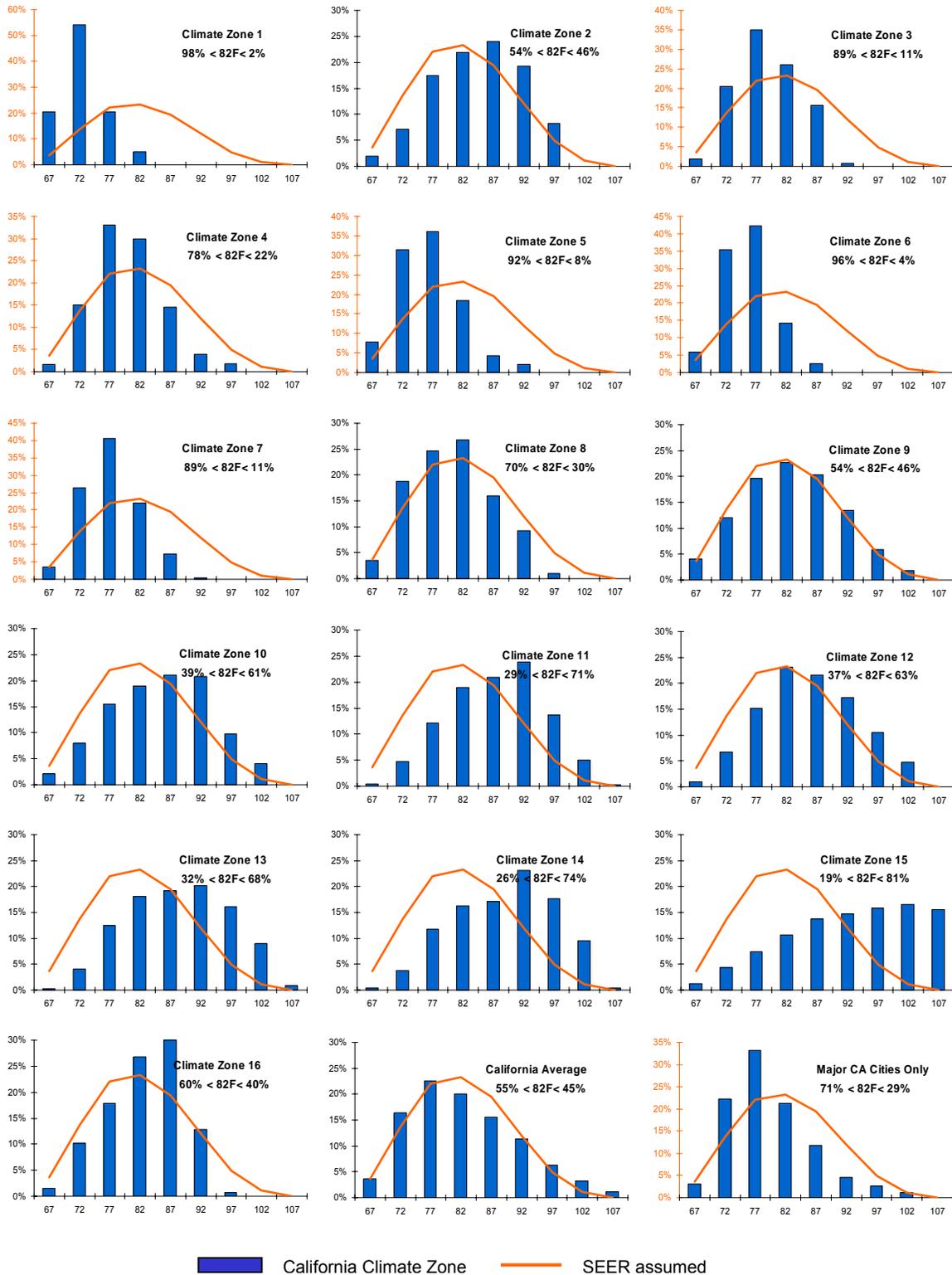


Figure 8 Distribution of Cooling Coil Load by California Climate Zones median single family residence, DOE-2 cooling loads



variable, omitted from Figure 9a was added to the model. Each new run adds a climate or house design variable to the previous runs, i.e., the effects are cumulative, such that the last case, Figure 9L, includes all effects omitted from Figure 9a. Figure 9L represents a much more realistic representation of the relationship between outdoor temperature and hourly cooling coil load than does Figure 9a. **Contrasting Figure 9a with 9L illustrates how differently cooling coil loads for typical house behave than is assumed by the SEER rating procedure and suggests reasons to anticipate potentially large variability in the ability of SEER to accurately predict cooling energy use in California residential applications.**

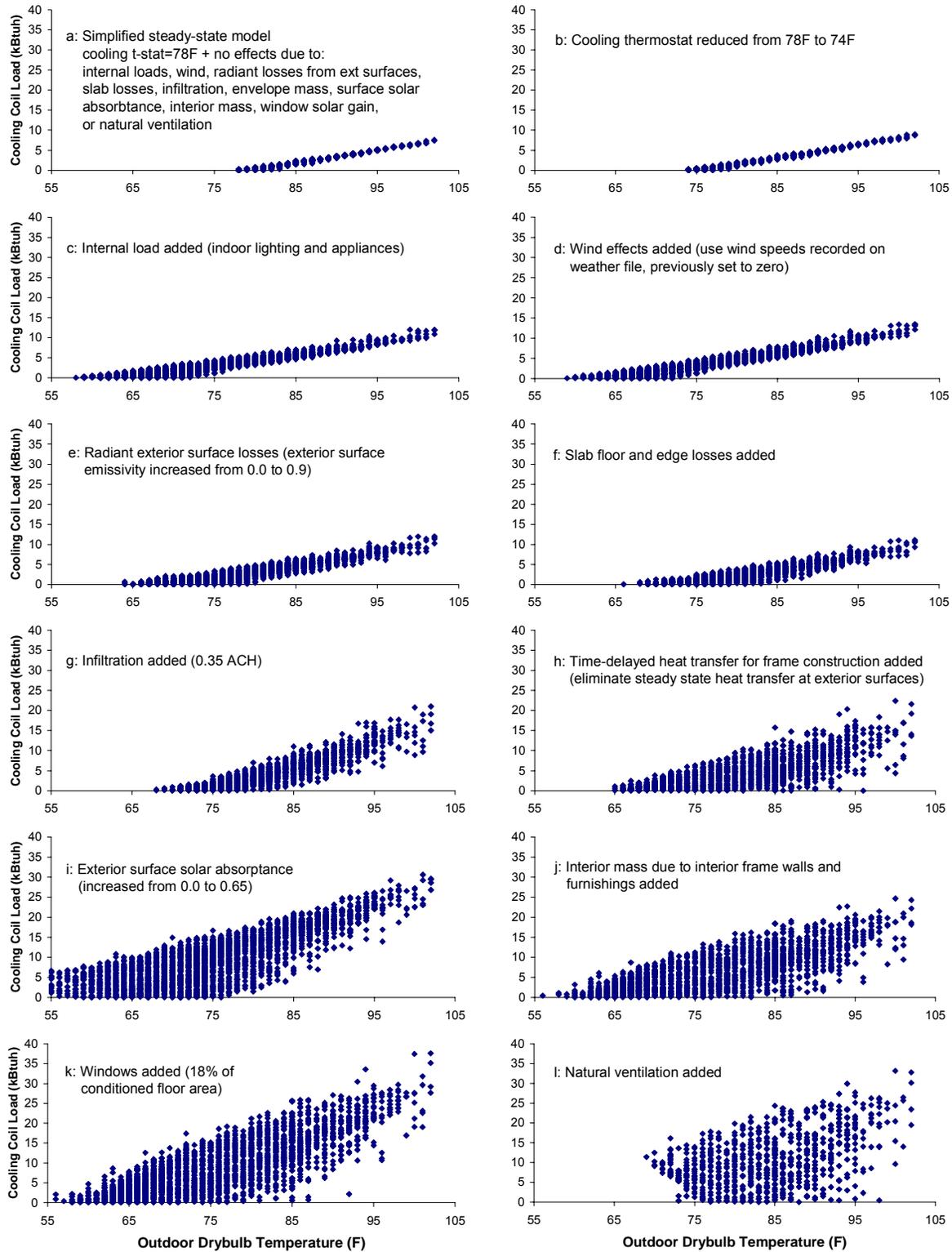
Each simulation case in Figure 9 is briefly described below.

- a) This is the simplest modeled case. It was devised to obtain a significantly linear relationship between in cooling coil load and outdoor temperature, similar to that which is implicit in the SEER rating procedure (compare Figure 3b). Numerous features of the more detailed (and realistic) model (case L) are omitted in this case. These include: cooling t-stat = 78F + no effects due to: internal loads, wind, radiant losses from ext surfaces, slab losses, infiltration, envelope mass, surface solar absorbtance, interior mass, window solar gain, or natural ventilation. In this first case, note that since there is no internal heat gains and no solar gains, the balance point is equal to the indoor thermostat setpoint (i.e., 78°F). The slope of the line is related to the building overall U_0 .
- b) Cooling thermostat was altered from 78°F in case “a” to 74°F. As expected, this shifts the balance point lower by 4°F, to 74°F.
- c) Internal loads due to interior lights and appliances are added to case “b”. Since these internal heat gains become “trapped” in the house, the balance point is shifted lower yet to approximately 57°F.
- d) Wind effects are “turned on”, i.e., wind speeds from the CZ09 weather file are used in the simulation. In the previous cases, wind speed was set to zero for all hours. The impact if this is small. It provides some cooling effects that cause a slight shift in the balance point (i.e., to approximately 58°F). It also “blurs” slightly (i.e., introduces additional variability into) the linear relationship between coil load and outdoor temperature.
- e) Longwave radiant exchange at exterior surfaces is “turned on”, i.e., the exterior surface emissivity for all exterior walls and roof surfaces are reset from 0 to 0.9. The impact of this is similar to the effect due to wind, but more significant, i.e., it provides some cooling effects that cause a slight shift in the balance point (i.e., to approximately 64°F). It also further “blurs” slightly the linear relationship between coil load and outdoor temperature.
- f) Slab edge losses are “turned on”. Similar to the previous two effects, this adds a further source of heat loss slightly raising the balance point.
- g) Infiltration, at a constant 0.35 air changes per hour, is added to case “e”. Due to the prior inclusion of internal loads, in case “g”, there are numerous cooling load hours when the outdoor temperature is cooler than the indoor temperature, hence, infiltration provides a cooling effect. Note that the general slope of the load-

temperature relationship has increased (become steeper) due to a significant additional means of heat loss).

- h) All exterior heat transfer surface constructions (i.e., walls and roofs) are converted from u-values (implies a steady-state $U \cdot A \cdot \Delta T$ calculation in the simulation) to use conduction transform functions (i.e., accounts for the time delay associated with the thermal mass of the roof and walls). All roof and wall construction are conventional wood frame. The u-values used in all previous cases were equivalent to the “delayed” constructions used in this and subsequent cases. The time delay of the heat gains through the envelope to the space further “blurs” the original straight line relationship between coil load and outdoor temperature.
- i) Solar absorptance is “turned on” at each exterior heat transfer surface, i.e., exterior surface solar absorptance is reset from 0 to 0.6 for roof and 0.7 for walls. This has the effect of adding additional heat gain to the space, hence the balance point decreased. Since solar gain is only very loosely correlated with outdoor temperature, this modification further blurs the relationship between coil load and outdoor temperature.
- j) Interior mass is “turned on” by using custom weighting factors in DOE-2 to calculate the unique contribution of the house interior walls and other surrounding surfaces plus furnishings to the overall capacitance (i.e., mass) of the spaces. In the previous runs, the DOE-2 “floor weight” was set very low, thus providing virtually instantaneous response between surface heat gain and space cooling load.
- k) Windows are added, predominantly on the north and south walls (18% of the conditioned floors area). This adds more heat gain which both lowers the balance point (although more modestly due to the effect of internal mass) and further corrupts the original relationship between load and outdoor temperature.
- l) Natural ventilation is enabled via the operable windows. This assumes a constant air change rate of 3 ACH whenever the indoor cooling load could be met using natural ventilation. If the entire cooling load could not be met using natural ventilation, the model assumed the windows were closed and the air conditioner was used to meet the cooling loads. The impact of natural ventilation is greatest on the coil loads that coincide with cooler outdoor temperatures, i.e., less than the 74°F thermostat temperature. The sloped boundary of the remaining cooling loads (i.e., starting at the X-axis near 74°F and toward the upper left) indicates that for hours with larger cooling loads, a greater temperature difference was necessary to provide the required cooling via natural ventilation to completely meet the load.

Figure 9 Cooling Coil Load as a Function of Outdoor Temperature
median single family residence, DOE-2 cooling loads, CZ09



4.5 Can DOE-2 be made to Match the SEER Rating Process?

Can a detailed simulation methodology such as is employed in DOE-2 reproduce the much more simplified assumptions implicit in the SEER methodology? See Table 3 and Figures 10 and 11.

A special DOE-2 simulation case was prepared in which much of the modeling sophistication of DOE-2 was simplified to match the SEER methodology. Key differences between the SEER methodology and DOE-2 and the changes needed to “force” DOE-2 agreement with the SEER assumptions are summarized in Table 3. In Table 3, items in blue font (with asterisks) indicate SEER assumptions that could not be replicated in DOE-2.

Table 3 Comparison of NIST & DOE-2 Calculation Methodologies

Calculation Assumptions	Cooling System Performance Assumptions*	
	SEER Rating Process	DOE-2 Program
Calculation Method	Steady-state from simplified bin analysis	Hour-by-hour simulation*.
Imposed Load Shape	Fixed	Example load profiles selected to closely match SEER assumptions. See Figure 10.
Cooling System Capacity	Fixed	Total cooling capacity as a function of outdoor temperature curve held constant
Cooling System Efficiency	Fixed value for at an outdoor temperature of 82°F with entering air at 80° F dry- bulb and 67 F wet- bulb.	Allow variation with outdoor dry-bulb only*. Eliminate wet-bulb dependency by creating curve-fit a fixed 67°F entering air wet-bulb.
Part-load performance	Assumes 50% cycling rate based on a fixed total cooling capacity	Varies with actual coil load and total capacity.*
Cooling System sensible-to-total ratio & Coil Load sensible-to-total ratio	Not addressed. Ratings and load based on total net capacity with no consideration of sensible and latent components	System sensible heat ratio set to 1.0. Effect of coil entering conditions on the cooling coil by-pass factor removed. Sensible capacity adjustment curve set to the total.
Cooling Coil Entering Conditions	Fixed at 80 F DB, 67 F WB	Fixed at 80 F DB, 67 F WB by setting capacity, efficiency, and by-pass performance curves to fixed ARI entering air conditions.

* Items in blue font (and with asterisk) indicate SEER assumptions DOE-2 could not replicate.

Mid-load temperatures and cooling load profiles for typical single-family California residences were found to varied widely as seen in Figure 8. Two cases having load profiles and mid-load temperatures similar to the SEER assumptions (Figure 10) were selected for further study since these will minimize any bias due to climate or building effects. In Figure 10, the two DOE-2 load profiles differ only by building orientation, i.e., north/south (mid-load temperature = 82.5 F) versus east/west (mid-load temperature = 84.5 F).

Figure 10 SEER Rating and DOE-2 Simulated Cooling Load Profiles

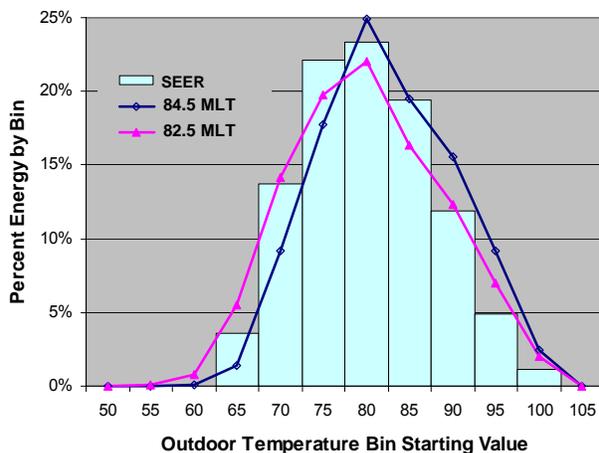
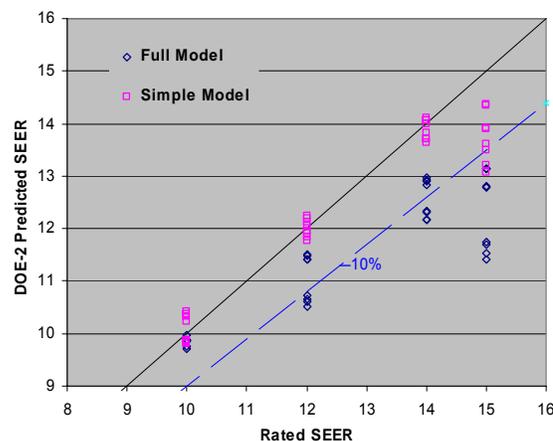


Figure 11 Effect of Simplified SEER Assumptions Rated SEER versus DOE-2 Predicted SEER



In Figure 11, the points noted as “Full Model” are DOE-2 simulation results that use performance curves based on manufacturer’s published data. Those points noted as the “Simple Model” are DOE-2 simulation results that have had their performance curves adjusted to match SEER assumptions as noted in Table 3 above. In particular, performance curves in the “Simple Model” are no longer dependent on cooling coil entering air conditions and produce performance values that would occur at cooling coil entering conditions of 80°F dry-bulb and 67°F wet-bulb.

In Figure 11, when DOE-2’s performance curves are “hobbled”, i.e., use simplified SEER assumed conditions (“Simplified Model”) rather than actual manufacture’s data (“Full Model”), the agreement between rated SEER and DOE-2 simulated SEER for single speed (SEER 10, 12 and 14) systems is good. When the simplified performance curves (“Simplified Model”) are replaced with manufacture’s realistic data (“Full Model”), rated SEER is over-predicts the more sophisticated (and realistic) simulation results.

The agreement for two-speed systems is not as good. It is likely that the residential load profiles produced in the DOE-2 simulations haven’t adequately reproduced the necessary load sequencing to replicate the rated SEER for two-speed units. Unfortunately, further exploration of this difference proved to be beyond the scope of the investigation.

Based on the results in Figure 11, it is clear that **for single-speed equipment, DOE-2 can closely reproduce the SEER rating methodology when similar simplifications are employed. These results also suggest that the SEER assumption regarding indoor coil entering conditions (i.e., 80°F dry-bulb and 67°F wet-bulb) may be a significant source of SEER bias in California residential applications.**

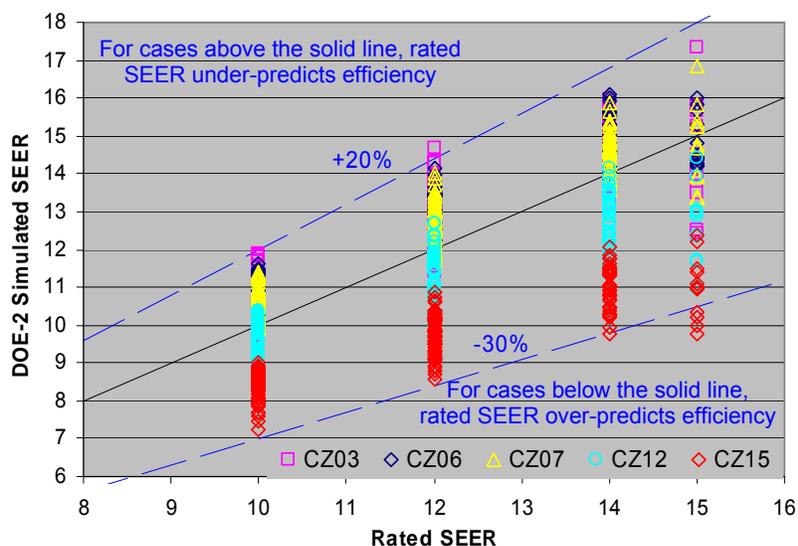
5.0 Findings that address the questions that guided the research

5.1 SEER as a Predictor of Residential Cooling Energy Use

Question 1: How effective is SEER as a predictor of expected annual cooling energy use in residential applications?

Figure 12 indicates that in residential California use, across the typical range of climate zones and across the typical range of house characteristics and HVAC system characteristics, **rated SEER predicts seasonal cooling efficiency only to within +20% to -30%**. The climate zones included in Figure 12 are five “indicator” climate zones. These represent the major population centers (Oakland – CZ03, Los Angeles – CZ06, San Diego – CZ07, and Sacramento – CZ12) plus climate zone 15 (Palm Springs). Cases that lie above the solid line (slope = 1.0) indicate that actual expected cooling efficiency (DOE-2-predicted SEER) exceeded the efficiency predicted by rated SEER, i.e., SEER under-predicted cooling efficiency. Cases that lie below the solid line indicate that SEER over-predicted cooling efficiency.

Figure 12: Rated SEER as a Predictor of Annual Cooling Efficiency
Single Family Residential Prototype, Five Representative California Climate Zones*
Min/Median/Max Building Characteristics, Min/Median/Max System Characteristics



* CZ03 (Oakland), CZ06 (Los Angeles), CZ07(San Diego), CZ12 (Sacramento) CZ15 (Palm Springs)

What is this variation due to?

This important question will be answered in term of three effects identified previously:

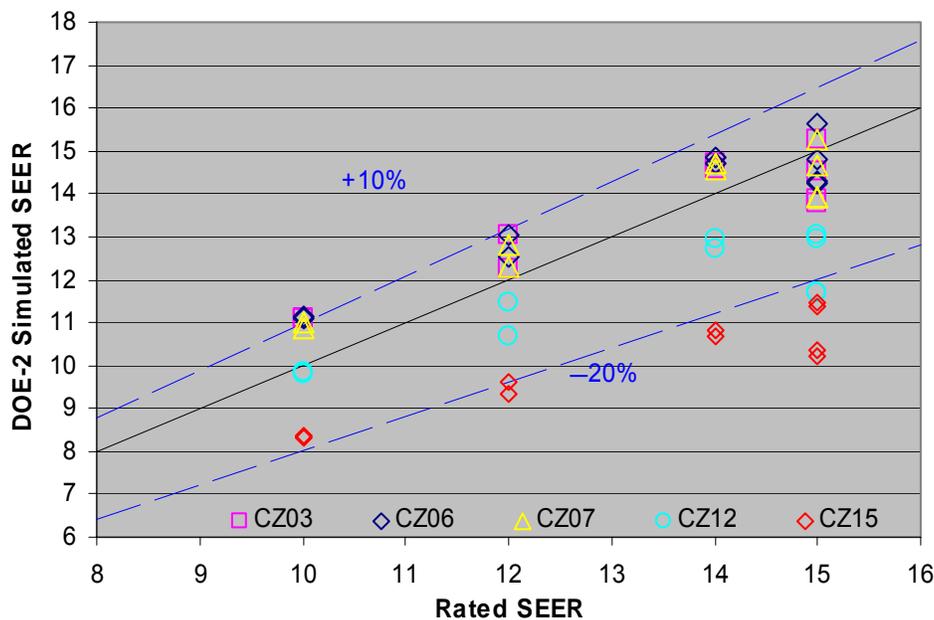
- Climate effects: simple correction factors were developed suitable for tabular application.
- Building effects: more complex corrections were investigated, but with less success than for climate
- System effects: more complex corrections were investigated, but with less success than for climate

5.2 Climate Effects in Residential SEER Bias

How much of the total variation in SEER-predicted residential energy use is due to climate zone effects, i.e., violations of the SEER-assumed standard climate?

In Figure 13, the results are limited to only median building characteristics (these differ by climate zone where required by Title 24) and median equipment characteristics (i.e., median cycling effects and sensitivity to climate) in order to estimate the average climate effect (by contrast, Figure 12 included min/median/max cases for both building characteristics and system characteristics). The variation in results in Figure 13 is +10% to -20%, reduced from the total variation (+20% & -30%) in Figure 12. Therefore, **on average, half to two-thirds of the total error in SEER in California residential applications appears to result from climate effects.** Note that this includes both the impacts due to outdoor temperature and indoor temperature (i.e., coil entering wet-bulb conditions). As in Figure 12, only the five indicator climate zones are included in Figure 13 (represent the major population centers plus Palm Springs (hot arid)). In Figure 13, one extreme of the range (where SEER is a conservative predictor of seasonal cooling energy efficiency) is represented by climate zones 3 or 6. The other extreme of the range of results (where SEER over-predicts seasonal cooling energy efficiency) is represented by climate zone 15. In several of the graphs that follow, only climate zones 6 and 15 are used to indicate the likely range resulting from climate effects.

Figure 13 Effect of Climate on Simulation-Estimated SEER
Single Family Residential Prototype, Five Representative California Climates
Median Building Characteristics, Median System Characteristics



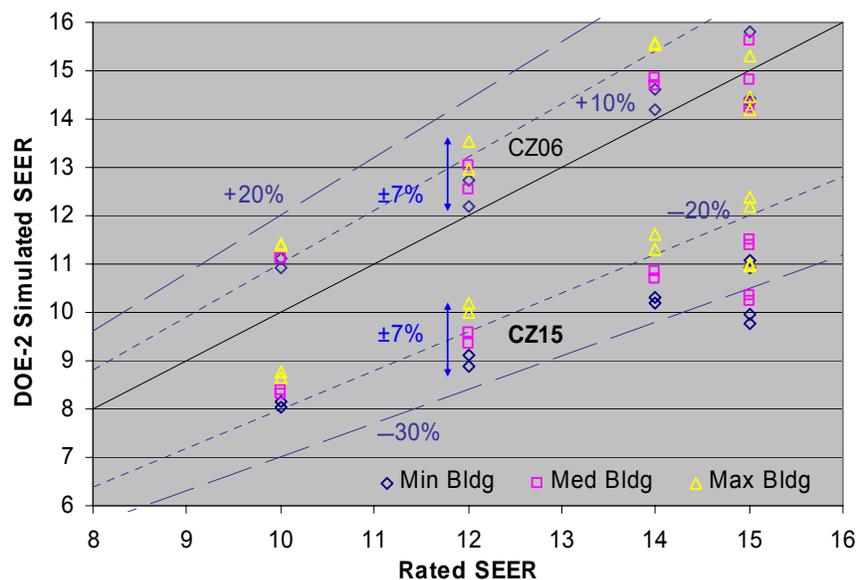
5.2 Building Effects in Residential SEER Bias

How much of the total variation in SEER-predicted residential energy use is due to variation in building characteristics that effect cooling coil load and its relationship with outdoor temperature? See Figure 14.

Figure 14 provides an estimate of building effects by including minimum, median, and maximum cases for building characteristics while holding equipment characteristics constant at median equipment cases only. Only results from climate zone CZ06 (Los Angeles, above the slope = 1.0 line) and CZ15 (Palm Springs, below the slope = 1.0 line) are shown. Fiducial marks from Figures 12 and 13 are also included for reference. The overall variation in Figure 14 (i.e., between climate zones) is less to that seen in Figure 12 since system effects are omitted but is very similar to the range of total variation in Figure 13 since the two climate zones in Figure 14 tend to bound the range of climate effects. **The $\pm 7\%$ variation within each climate zone is due to building effects and accounts for a little over half of the variation not attributable to climate effects or about one-fourth to one-fifth of the total variation.** This is largely through the impact that building characteristics have on mid-load temperature (via the building balance point). The effects appear to be of similar magnitude for both mild and hot arid climates, hence, there appears to be no significant interaction between the climate and building effects. The building characteristics that were allowed to vary in Figure 14 are listed below.

Total Floor Area	Number of Stories	Aspect Ratio	Occupancy Density
Internal Gains	Cathedral Roof %.	Floor Type	Window Area
Glass U-value	Glass SHGC	Wall Insulation	Roof Insulation
Crawlspace R-Value	Slab Perim. Insul.	Duct Leakage	Duct Insulation
Exterior Shading	Infiltration Rate	Natural Ventilation	Cool T-Stat Setpoint

Figure 14 Effect of Building Characteristics on Simulation-Estimated SEER Single Family Residential Prototype, Climate Zones 6 (mild) and 15 (hot arid) Min/Median/Max Building Characteristics, Median System Characteristics



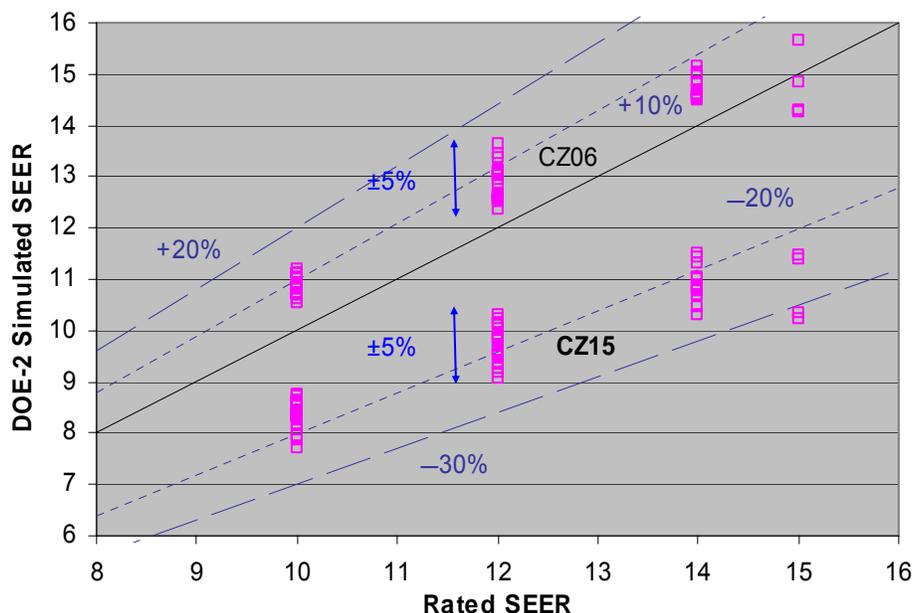
5.3 System Effects in Residential SEER Bias

How much of the total variation in SEER-predicted residential energy use is due to variation in individual HVAC system characteristics (i.e., the scatter in Figure 1)?

See Figure 15.

The results in Figure 15 estimate of system effects by including minimum, median, and maximum cases for system characteristics while holding building characteristics constant at median levels. Only results for climate zone CZ06 (Los Angeles) and CZ15 (Palm Springs) are shown since these tend to bound the total scatter due to climate effects. Fiducial marks from Figures 12 and 13 are also included for reference. The overall variation in Figure 15 (i.e., between climate zones) is less to that seen in Figure 12 since building effects are omitted but is very similar to the range of total variation in Figure 13 since the two climate zones in Figure 14 tend to bound the range of climate effects. **The $\pm 5\%$ variation within each climate zone is due to system effects (e.g., individual system differences sensitivity to outdoor temperature and to cycling degradation) and accounts for a little less than half of the variation not attributable to climate effects or about one-fifth to one-sixth of the total variation.** The effects appear to be of similar magnitude for both mild and hot arid climates, hence, there appears to be no significant interaction between the climate and system effects. The system characteristics that were allowed to vary in Figure 14 were sensitivity to outdoor condensing temperature and sensitivity to cycling effects.

Figure 15 Effect of HVAC System Characteristics on Simulation-Estimated SEER
Single Family Residential Prototype, Climate Zones 6 (mild) and 15 (hot arid)
Median Building and Expanded Equipment Prototypes

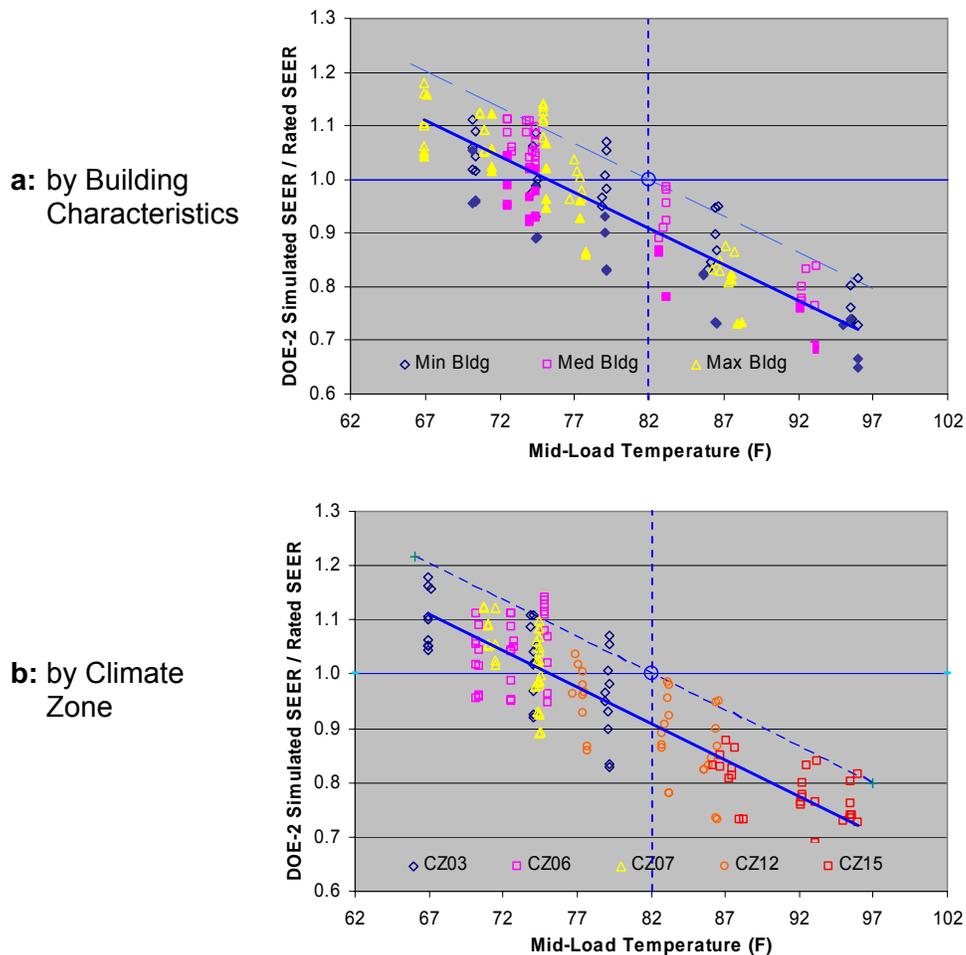


5.4 What mid-Load Temperature for California?

Can these simulation results recommend an improved mid-load rating temperature for California residential applications? See Figure 16.

Figure 8 indicated that the mid-load temperatures for a median single-family house could vary widely between California climate zones and that the average mid-load temperature for the major California urban areas was approximately 76°F, rather than 82°F. Figure 16 provides an alternate view of the range in mid-load temperature for the typical range of single-family residences across representative California climates. In Figure 16, building (a) and climate (b) effects contribute to the wide variation in mid-load temperature (system characteristics are restricted to median systems only). Note that a best fit line (bold solid blue) passes through the line where DOE-2 simulated SEER equals rated SEER at approximately 75°F rather than 82°F (i.e., as does the dashed line), which more nearly agrees with the results from Figure 8. **These results suggest that for California residential applications, 75°F would serve as a better SEER rating temperature, but that the required mid-load rating point varies considerably with both building characteristics and climate.**

Figure 16 Effect of Climate and Building Characteristics on Mid-Load Temperature
 Single Family Prototype, Five Representative California Climates
 Min/Median/Max Building Characteristics, Median System Characteristics

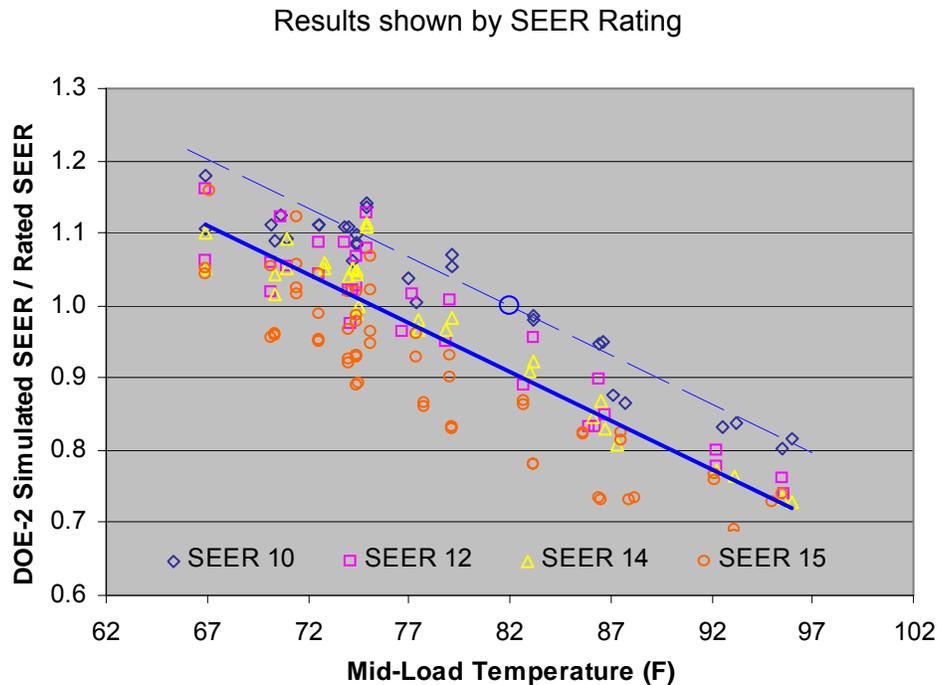


5.5 The Role of Indoor Coil Entering Conditions

What other effects tend to bias SEER-predicted energy use in California residential applications? See Figure 17.

Figure 17 presents the same results shown in Figure 16, however, in Figure 17 the results are color coded by SEER rating. In Figure 17, it is evident that SEER 10 systems lie close to the hypothetical best fit line that passes through 82°F (the dashed line) while systems with higher SEER ratings fall below this line. The higher the SEER rating, the further the results fall below the hypothetical best fit line through 82°F. While a more thorough investigation of this observation was beyond the scope of this study, this bias is similar to that seen in Figure 11 where **simplified SEER assumptions, largely regarding indoor coil entering conditions, appeared to provide a systematic bias of similar sign and magnitude.** For example, in Figure 11, the use of more realistic coil entering conditions resulted in rated SEER under-predicting DOE-2 simulated SEER by 10% or more. This is similar to the vertical shift between the best fit line and the dashed line passing through 82°F in Figure 17.

Figure 17 Effect of Climate and Building Characteristics on Mid-Load Temperature Single Family Expanded Prototype, Five Representative California Climates
Min/Median/Max Building Characteristics, Median System Characteristics



5.6 Climate Effects SEER Correction Factors

What corrections can be applied to these results (e.g., Figure 13) to allow SEER to more accurately predict energy use in California Climates? Figure 18 shows the results of applying an empirical climate zone multiplier (DOE-2 simulated SEER / rated SEER, for each climate zone, see Table 4). Comparing to Figure 13, **using the climate zone multipliers reduces the variation in SEER-predicted annual energy use from +10% and -20% to ±6%**. It is important to note that these climate zone correction multipliers implicitly address both the impacts due to outdoor temperature and indoor temperature (i.e., coil entering wet-bulb conditions). Residential climate zone SEER multipliers for all California climate zones are provided in Table 5 (next page).

Figure 18 Climate Zone-Adjusted SEER as a Predictor of Annual Cooling Efficiency
Single Family Residential Prototype, Representative California Climates
Median Building Characteristics, Median System Characteristics

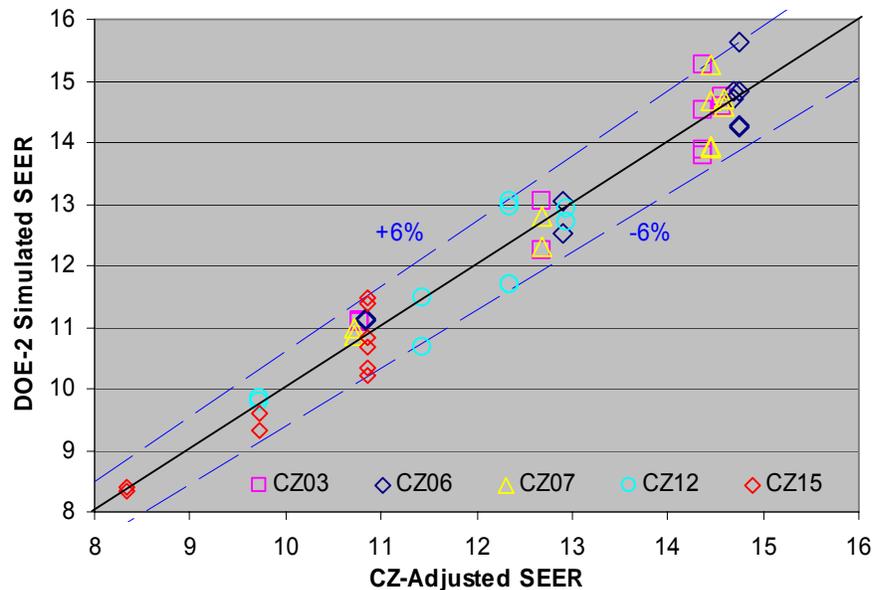


Table 4 Residential SEER Climate Zone Multipliers Used in Figure 18
Single Family Residential Prototype, Five Representative California Climates
Median Building Characteristics, Median System Characteristics

	Single-Speed SEER Rating			All Single-Speed	Two-Speed	All Units
	10	12	14			
CZ03	1.08	1.06	1.04	1.07	0.99	1.06
CZ06	1.08	1.07	1.05	1.07	1.02	1.07
CZ07	1.07	1.06	1.04	1.06	1.00	1.06
CZ12	0.97	0.95	0.92	0.95	0.87	0.94
CZ15	0.83	0.81	0.78	0.82	0.76	0.81

* Multipliers assume rated fan energy and system sizing consistent with the SEER ratings procedure.

Table 5 Residential SEER Climate Zone Multipliers for All California Climate Zones
Single Family Residential Prototype, All California Climates
Median Building Characteristics, Median System Characteristics

	Single-Speed SEER Rating			All Single-Speed	Two-Speed
	10	12	14		
CZ01	1.16	1.16	1.14	1.15	0.98
CZ02	0.97	0.95	0.92	0.95	0.83
CZ03	1.08	1.06	1.04	1.07	0.99
CZ04	1.07	1.04	1.03	1.05	0.93
CZ05	1.07	1.07	1.04	1.06	0.96
CZ06	1.08	1.07	1.05	1.07	1.02
CZ07	1.07	1.06	1.04	1.06	1.00
CZ08	1.07	1.06	1.04	1.02	0.95
CZ09	0.99	0.97	0.95	0.97	0.85
CZ10	0.95	0.94	0.90	0.93	0.81
CZ11	0.92	0.90	0.86	0.90	0.78
CZ12	0.97	0.95	0.92	0.95	0.87
CZ13	0.93	0.91	0.88	0.91	0.78
CZ14	0.88	0.85	0.82	0.85	0.75
CZ15	0.83	0.81	0.78	0.82	0.76
CZ16	1.05	1.03	0.99	1.03	0.84

** These multipliers are used to adjust SEER ratings for a selected SEER-rated system.*

5.7 2001 Title 24 SEER Correction Factors

How do the results from these empirical corrections for California climate zones compare with the temperature corrected SEER's currently included in 2001 Title 24? See Figure 19.

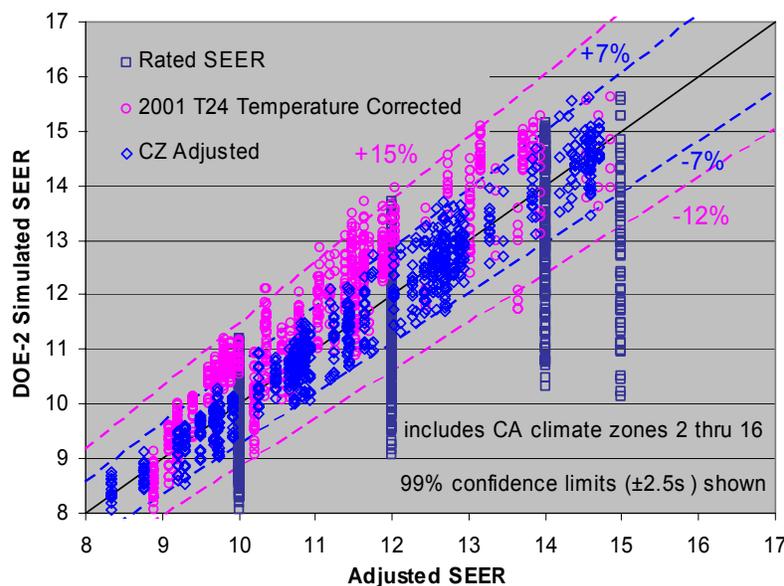
Figure 19 compares the ability to predict anticipated actual SEER (i.e., DOE-2-simulated SEER) using the following three “methods”. Note that Figure 19 includes all California climates except climate zone 1 (omitted due to limited cooling requirements) and min/median/max systems. 99% confidence limits (limits containing 99% of the cases) are also shown for the corrected results.

- rated SEER (no correction applied),
- temperature corrected SEER (from 2001 Title 24), and
- climate zone corrected SEER (from this research).

The results presented in Figure 19 indicate the following:

- rated SEER estimates of anticipated actual SEER can vary substantially but these results indicate a bias that tends to over-predict efficiency in California residential applications, i.e., anticipated actual SEER tends to be less than rated SEER
- Title 24 temperature corrected SEER significantly improves upon rated SEER (+15% to -12%), but results indicate a bias that tends to under-predict efficiency, i.e., anticipated actual SEER tends to be better (greater) than Title 24 temperature corrected SEER
- climate zone corrected SEER (this research) further reduces variation in estimating anticipated actual SEER, however, predicted results vary by $\pm 7\%$ (slightly more than in Figure 18 since min/median/max systems are included in Figure 19).

Figure 19 Title 24 Temperature Corrected SEER versus Climate Zone Adjusted SEER
Single Family Residential Prototype, All California Climate Zones
Median Building Characteristics, Min/Median/Max System Characteristics



5.8 More Detailed SEER Correction Factors

Is there significant potential for more detailed correction procedures? See Figure 20.

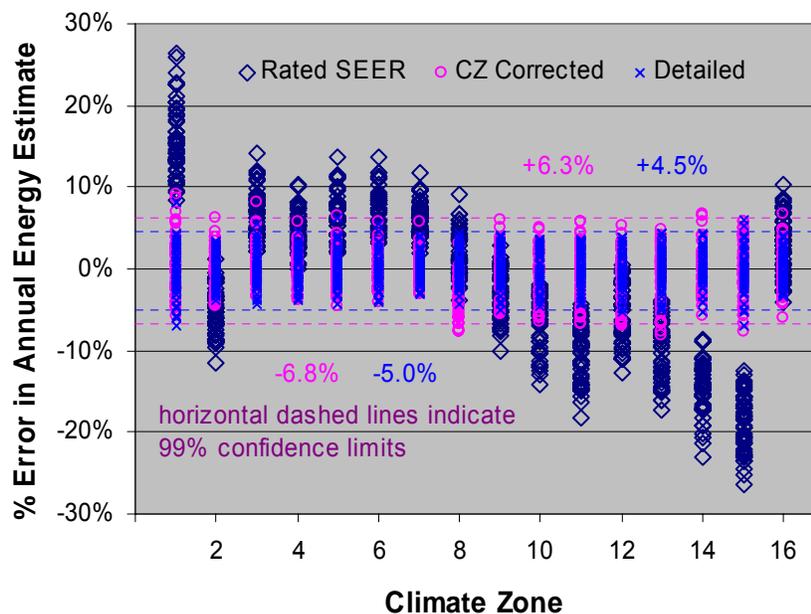
Figure 20 compares the relative error associated with the following:

- rated SEER (no correction applied),
- climate zone corrected SEER — simple empirical correction (from Table 4 above).
- detailed SEER correction model — applies only to single-speed equipment and includes terms based on C_D (degradation coefficient as determined in SEER cycling tests), mid-load temperature (determined from an empirical look-up table based on previous simulation cases), sensitivity of the system's efficiency to changing coil entering wet-bulb, and the system's sensible heat ratio. (For more details, see the full report).

The results presented below indicate the following:

- relative error associated with using rated SEER to estimate annual energy use (i.e., DOE-2 simulated SEER) can vary substantially — the 99% of the simulated cases lie between +20% and -23%.
- using climate zone corrected SEER to estimate annual energy use significantly reduces relative error — the 99% of the simulated cases lie between +6.3% and -6.8%.
- **the detailed SEER correction model single-speed residential cooling energy use further reduces relative error only modestly, i.e., from $\pm 6\%$ to $\pm 4.5\%$ to 5.0%**

Figure 20 Relative Error Due to:
Rated SEER, Climate Zone Adjusted SEER & Detailed Adjusted SEER
Single Family Residential Prototype, All California Climate Zones
Median Building Characteristics, Min/Median/Max System Characteristics



5.9 SEER as a Predictor of Residential Cooling Energy Savings

QUESTION 2: How effective is SEER as a predictor of expected annual cooling energy savings in single family residential applications?

Previous results indicate potentially large uncertainties in using rated SEER to anticipate annual cooling energy use in residential applications in California climates. Arguably, SEER is more frequently used to anticipate the *reduction* in annual cooling energy when upgrading from an HVAC system with a lower SEER rating to a system with a higher SEER rating, e.g., from a SEER 12 system to a SEER 15.

Figure 21 shows the results of upgrading from one SEER level to a higher SEER level. Five HVAC system upgrade cases are reported in Figure 21, e.g., SEER 10 to SEER 12, SEER 10 to SEER 14, etc. The upgrade cases are labeled along the X-axis, both in terms of the assumed SEER ratings and the total number of SEER “points” involved in the upgrade. Expected savings are shown in the left-most vertical bar (dark blue) for each upgrade case. This is the savings one should expect if rated SEER were a reliable indicator of cooling energy use.

Note that the calculation of SEER-predicted savings can be counter-intuitive for at least two reasons. First, to achieve a *reduction* in cooling energy consumption, the SEER value must *increase*. Second, the percentage *increase* in SEER (see Equation 1 below) does NOT indicate the anticipated percent *reduction* in cooling energy (i.e., savings) due to SEER upgrade (Equation 2 below).

Example calculation of the percentage improvement in SEER (Equation 1) and the percent reduction in annual cooling energy use due to an improvement in SEER

If a home owner or builder is considering the purchase of a SEER 14 cooling system, rather than a minimally compliant system (SEER 10), what is the percent improvement in SEER and what should be the resulting annual savings in cooling energy?

Improvement in SEER:

$$\left(\frac{SEER_{14}}{SEER_{10}}\right) - 1 = 1.40 - 1 = 0.40 \dots \text{a } \mathbf{40\% \text{ improvement in SEER}} \quad (1)$$

Anticipated reduction in annual energy use due to a SEER improvement:

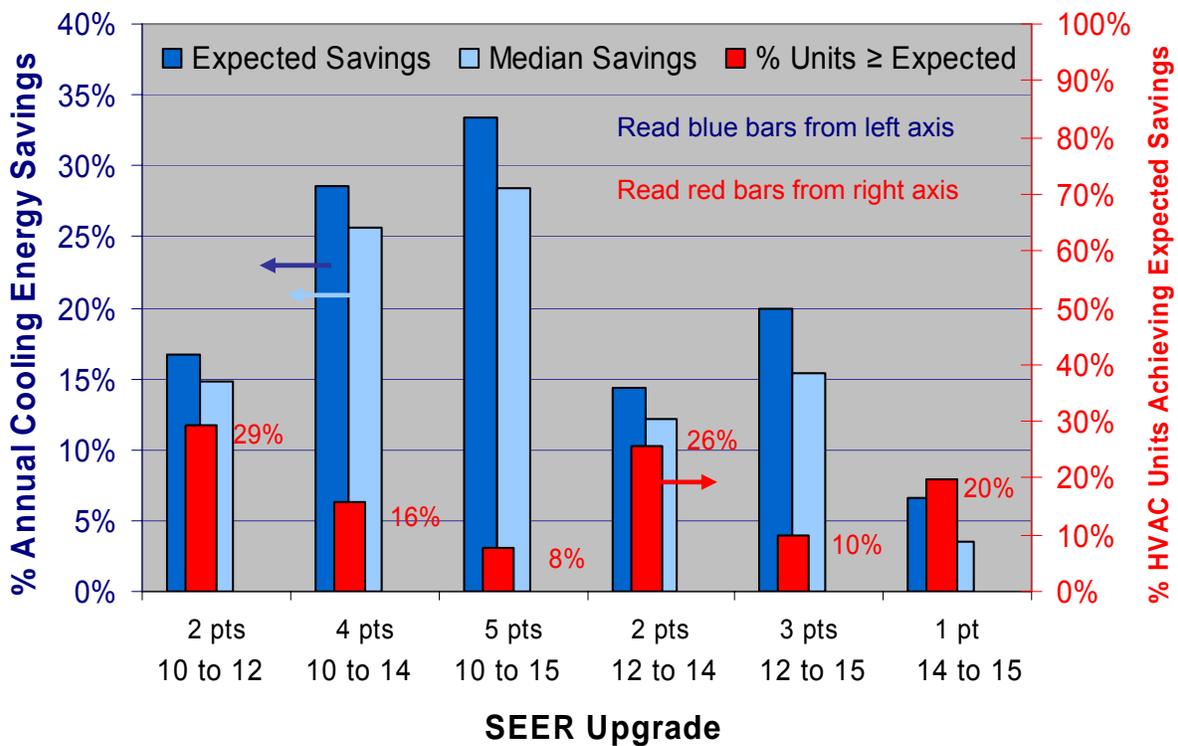
$$1 - \left(\frac{1}{\frac{SEER_{14}}{SEER_{10}}} \right) = 1 - \left(\frac{SEER_{10}}{SEER_{14}} \right) = 1 - 0.714 = 0.286 \dots \text{a } \mathbf{29\% \text{ reduction in energy use}} \quad (2)$$

This 40% improvement in SEER should yield a 29% reduction in annual cooling energy use.

Figure 21 also presents the median savings achieved using the DOE-2 simulations (light blue bar). For each upgrade case, it is evident that on average actual cooling energy savings falls short of the expected savings. This variation results from differing levels of sensitivity by individual units to indoor and outdoor conditions. Much of this variation in individual systems was illustrated in Figure 1.

An additional result of interest in Figure 21 is indicated in red font and red vertical bars (read these bars against the RIGHT axis). These indicate the percentage of the simulated cases where the SEER-predicted (“expected”) level of savings was achieved or exceeded. These results indicate that **in residential applications, 75% to 90% (i.e., one minus the red numbers reported in Figure 21) of the times consumers upgrade from a minimum efficiency HVAC system, their actual annual cooling energy savings will fall short of the level indicated by rated SEER.** In general, the larger the SEER upgrade, e.g., from SEER 10 to SEER 15, the lower the probability of achieving the expected savings.

Figure 21: Percentage Savings Achieved by SEER Upgrade in Residential Applications (Upgrading from a Lower SEER System to a Higher SEER System)
Single Family Residential Prototype, All California Climate Zones
Min/Median/Max Buildings, Min/Median/Max Systems

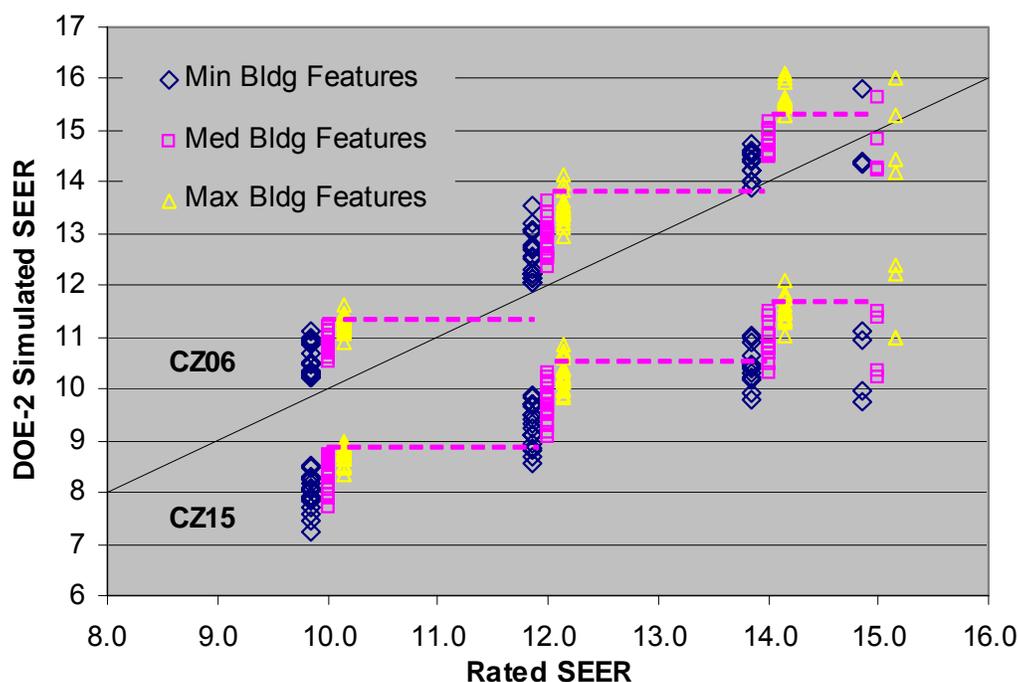


5.10 SEER as a Predictor of Residential *Relative* Cooling Energy Savings

QUESTION 3: How effective is SEER in ranking the seasonal cooling efficiency of different SEER-rated HVAC systems? See Figure 22.

Like the EPA gas mileage label, “your mileage may vary”, actual seasonal cooling efficiency (SEER) may vary due to user effects such as thermostat setpoint or differences between houses such as amount of glass, shading, and orientation. Notwithstanding this, can SEER be used to compare the *relative* cooling performance of SEER-rated HVAC systems? For example, for a specific house and climate zone, will a SEER 11 unit reliably use less annual cooling energy than a SEER 10 unit? In Figure 22, the worst simulated SEER among the range of results for a more efficient system (i.e., the system with a higher SEER rating) should be better (i.e., greater) than the best simulated SEER among the range of results for the less efficient system (i.e., the system with the lower SEER rating). In other words, there should be no “overlap” in the vertical range of simulated SEER results from a less efficient system to a more efficient system. Figure 22 indicates that **to assure savings, one must upgrade at least two SEER points**. Figure 22 also indicates there is a greater potential for concern in warmer climates.

Figure 22 Reliability of SEER* in Ranking the Relative Savings of HVAC Systems
Single Family Residential Prototype, Climate Zones 6 (mild) and 15 (hot arid)
Min/Median/Max System Characteristics



* *rated SEER values in Figure 22 have been slightly juxtaposed to improve legibility. Actual rated SEER values are integer values.*

Looking more closely, the data in Figure 22 allows this question of reliability of SEER as an indicator of relative efficiency to be answered from two different perspectives:

Consumer perspective — the individual consumer is likely to be concerned about a cooling system upgrade to a specific house, i.e., to upgrade a system on an existing house or on a new home purchase. From the individual consumer's perspective, it is most appropriate to focus only on the results for the median houses, i.e., in Figure 22 examine the vertical ranges of the median building results (within a climate zone).

Regulatory perspective — the regulatory perspective must consider the reliability of SEER as an indicator of relative efficiency across a population of houses, whose characteristics will vary, i.e., in Figure 22 examine the vertical ranges across all building results (within a climate zone).

From the perspective of an individual consumer, i.e., for a specific house, Figure 22 indicates that one must upgrade at least two SEER points to be assured of savings. From the regulatory perspective, i.e., across all houses in a climate zone, the answer appears to be that even upgrading two SEER points will not necessarily assure savings. From both points of view, SEER is a more reliable predictor of relative efficiency in cooler climates than in warmer climates.

5.11 SEER as a Predictor of Residential Cooling Peak Demand

QUESTION 4: How effective is SEER as a predictor of expected cooling peak demand and demand savings in single family residential applications? See Figures 23 and 24 on the following pages.

This question has always been of greatest interest to the utilities and state energy regulators and has become all the more important since ARI (Air-Conditioning and Refrigeration Institute) decided in November of 2002 to stop listing EER for SEER-rated units in its directory of certified equipment.

Analogous to the climate zone correction multipliers for SEER presented in Table 5, climate zone correction multipliers for rated EER were also developed and are presented in Table 6.

Table 6 Residential EER Climate Zone Multipliers for All California Climate Zones
Single Family Residential Prototype, All California Climates
Median Building Characteristics, Median System Characteristics

	Single-Speed SEER Rating			All Single-Speed	Two-Speed
	10	12	14		
CZ01	1.26	1.30	1.29	1.29	1.28
CZ02	1.08	1.04	1.02	1.05	1.14
CZ03	1.17	1.17	1.15	1.17	1.21
CZ04	1.10	1.10	1.07	1.10	1.18
CZ05	1.18	1.19	1.16	1.18	1.23
CZ06	1.20	1.20	1.19	1.20	1.23
CZ07	1.17	1.18	1.17	1.17	1.25
CZ08	1.17	1.18	1.17	1.10	1.25
CZ09	1.10	1.07	1.07	1.07	1.11
CZ10	1.05	1.01	0.98	1.01	1.10
CZ11	1.03	0.98	0.94	0.99	1.07
CZ12	1.03	1.01	0.99	1.01	1.10
CZ13	1.01	0.99	0.95	0.99	1.06
CZ14	1.02	0.97	0.92	0.97	1.07
CZ15	0.94	0.89	0.85	0.90	1.02
CZ16	1.10	1.09	1.05	1.09	1.14

** These multipliers are used to adjust EER ratings for a selected SEER-rated system (if the EER rating is available).*

Figure 23 and 24 on the following pages illustrate and compares the success of four ways to predict peak cooling demand in residential applications.

- a) rated SEER, from manufacturer's test at 82°F,
- b) rated EER (from manufacturer's test at 95°F),
- c) climate zone corrected SEER (using empirical tabular SEER multipliers developed in this research), and
- d) climate zone corrected EER (using empirical tabular EER multipliers developed in this research)

Figure 23 reports EER at DOE-2 simulated HVAC peak. Figure 24 reports DOE-2 simulated HVAC peak demand (in kW/ton). In both figures, the cases are labeled as enumerated above. For case (b), rated EER, the results are color coded first by climate zone, then by SEER. Where the cases are color coded by climate zone, this is done to help distinguish the range in the results across all climates and within a specific climate zone.

Based on the results in Figure 23, the following can be concluded regarding the effectiveness SEER as a predictor of expected cooling peak demand and demand savings in single family residential applications:

- e) **The variation in rated SEER agreed with the variation in peak EER only to within +15% and –30% of anticipated actual EER.** Interestingly, SEER appears no worse, perhaps slightly better at predicting EER than SEER (compare with results in Figure 12).
- f) **Rated EER (from manufacturer's test at 95°F) was able to predict actual EER to within +23% and –15%.** Two "views" of these results are provided. Figure 23-b1, (color-coded by climate zone) indicates that rated EER under-predicts actual EER for the milder climate zones and over-predicts actual EER for the hotter climate zones. Figure 23-b2, (color-coded by rated SEER) indicates that the ability of rated EER to predict actual EER is similar among the single-speed systems (i.e., the SEER 10, 12, and 14 systems in Figure 23-b2), but is quite different for the two-speed systems (SEER 15 systems). The SEER 15 systems tend to be rated with a disproportionately low EER (e.g., the EER of the SEER 15 systems were similar to the best SEER 10's and the worst SEER 12's). Fortunately, Figure 23-b2 also indicates that the SEER 15 units tend to outperform their EER ratings (i.e., the EER ratings for the SEER 15 systems tend to underestimate their actual EER).
- g) **Climate zone corrected SEER (i.e., from Table 5) was able to predict actual EER to within +12% and –15%.** This result is provided only as a matter of reference. The climate zone correction factors in Table 5 are not recommended for use with estimates of EER.
- h) **Climate zone corrected EER (i.e., from Table 6) was able to predict actual EER to within +7% and –7%.**

Figure 23: SEER and EER as Predictors of EER at HVAC Peak Demand
 Single Family Residential Prototype, All California Climate Zones (except CZ01)
 Median Building Characteristics, Min/Median/Max System Characteristics

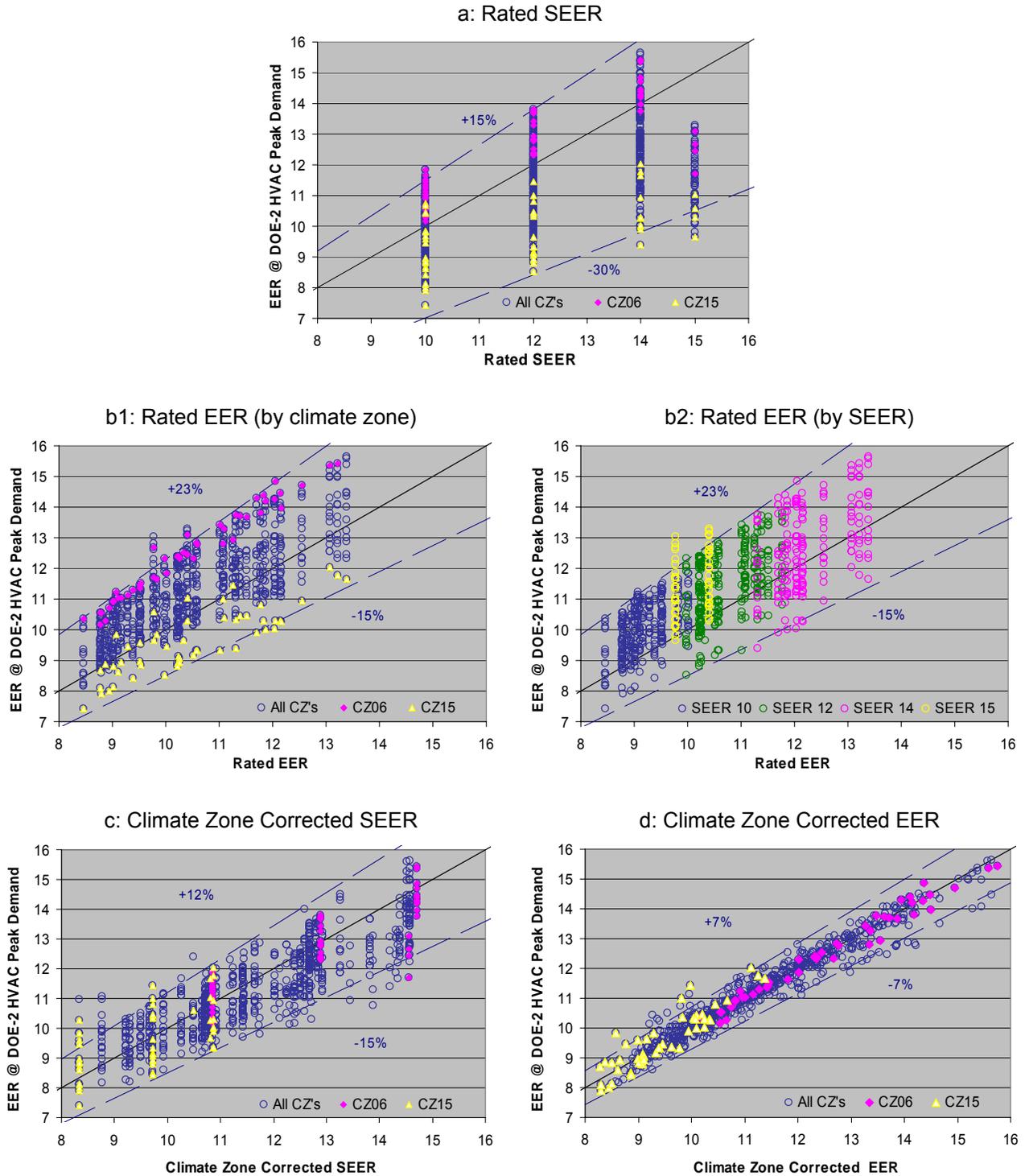
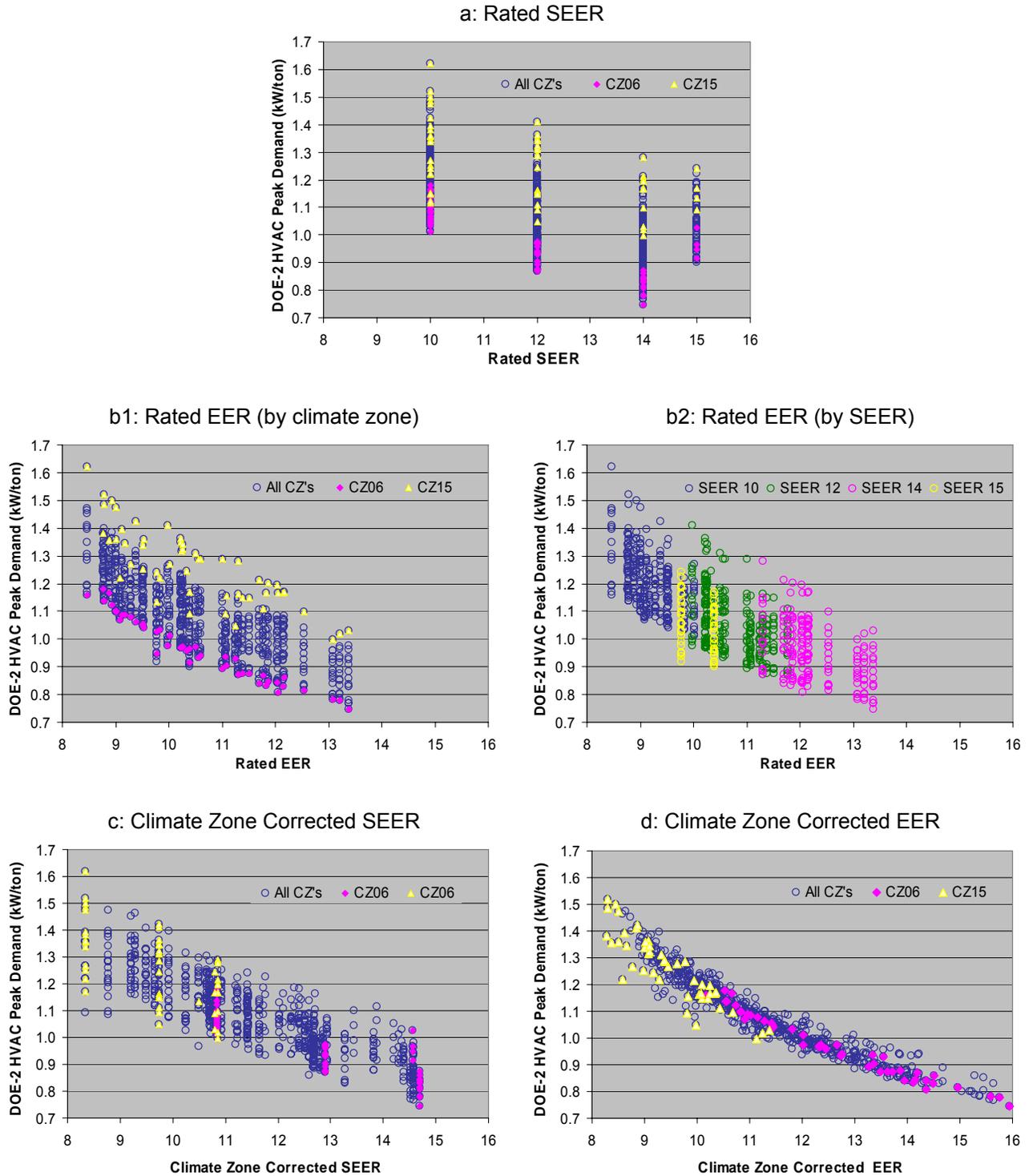


Figure 24: SEER and EER as Predictors of HVAC Peak Demand
 Single Family Residential Prototype, All California Climate Zones (except CZ01)
 Median Building Characteristics, Min/Median/Max System Characteristics



5.12 SEER as a Predictor of *Non-Residential* Cooling Energy Use

How effective is SEER as a predictor of expected annual cooling energy use in non-residential applications? See Figure 25.

The study revealed VERY different findings for residential versus non-residential applications. These differences were associated with differences in the building use and system operation, rather than the buildings or cooling systems themselves. In non-residential applications, building use and system operation more grossly violate the fundamental SEER rating assumptions than in residential applications.

In the non-residential applications, the most significant violation of SEER rating process assumptions was related to the operation of the indoor fan.

- In non-residential applications, the indoor fan operated continuously during occupied hours, to provide code-mandated ventilation air.
- For residential applications, the indoor fan was assumed to cycle with the compressor operation.

Figure 25 illustrates the impact indoor fan operation had on annual cooling-efficiency (DOE-2 predicted SEER). In Figure 25a, the continuously operating fans are included in the simulated SEER. **With indoor fan energy included, rated SEER very significantly over-predicts annual cooling efficiency, e.g., simulated SEER is approximately half of rated SEER.**

Figure 25b presents the same data from Figure 25a, however, indoor fan energy is not included in the calculation of the DOE-2 simulated SEER (i.e., condensing unit SEER).

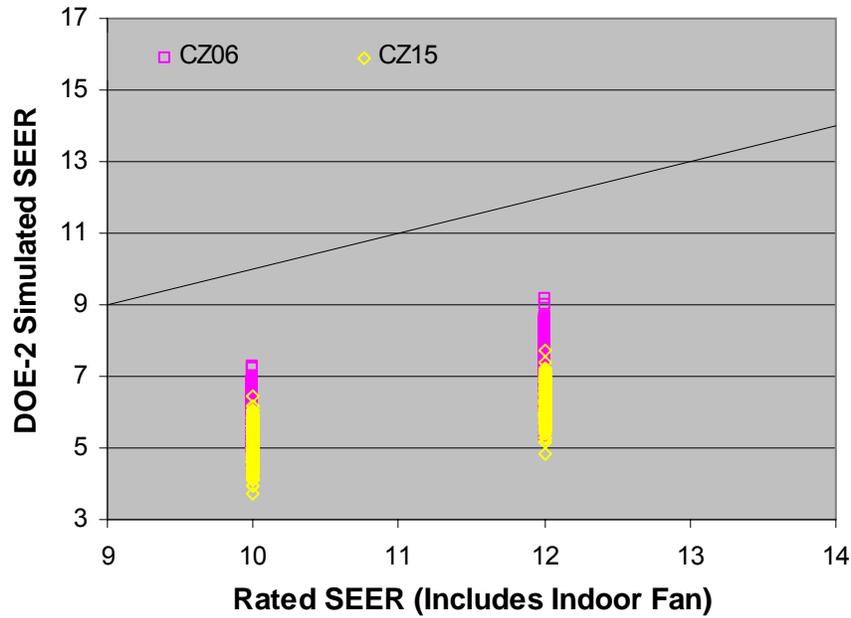
Once indoor fan energy was excluded, the non-residential results more nearly resembled residential results, however, significant remaining differences included:

- **influence of ventilation air,**
- **the greater range in non-residential building balance point due to the potential for much greater solar gain and internal load, and**
- **use of core versus perimeter zoning.**

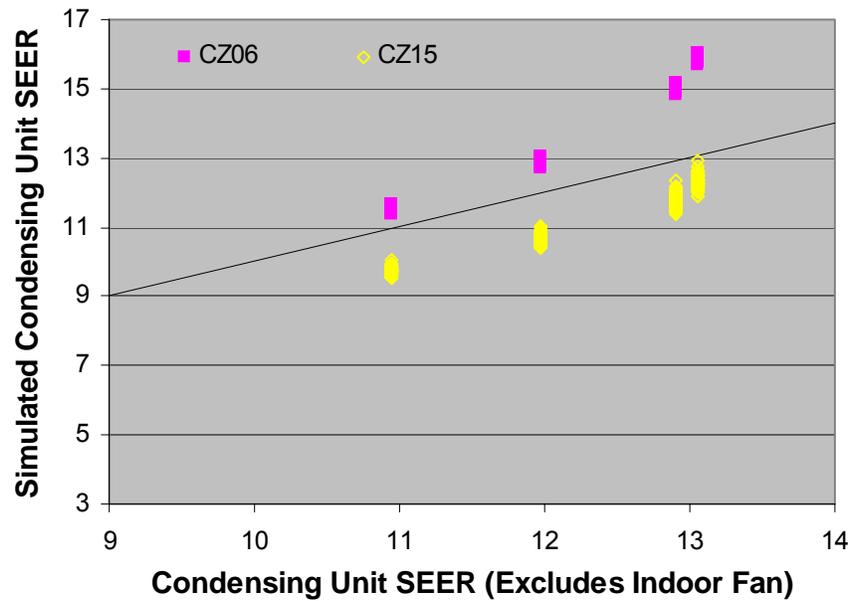
Similar results were obtained for the other non-residential prototypes (small retail, school classroom, and portable classroom). The interested reader is referred to the full report for a detailed discussion of both the residential and non-residential results.

Figure 25: Rated SEER as a Predictor of Annual Cooling Efficiency
 Small Office Prototype, Climate Zones 6 (mild) and 15 (hot arid)
 Median Building Characteristics, All Zones, Min/Median/Max System Characteristics

a: Indoor Fan Energy Included



b: Indoor Fan Energy Excluded



6.0 Summary of Findings

- Neither SEER nor EER is a sufficiently reliable indicator of cooling energy performance (consumption or demand) to meet the needs of California stakeholders. In residential applications, system efficiency upgrades will fall short of expected levels 75% to 90% of the time. Non-residential applications are more complex and require substantial additional research, but indications are that an even larger fraction will fall short of expected savings.
- Most of the basic assumptions implicit in the SEER rating process were found to be a poor match for typical California applications. As a result, the overall error or bias associated with using rated SEER to anticipate seasonal energy efficiency in California residential applications is approximately +20% (in milder climates) to -30% (in warmer climates). This overall bias was partitioned into the following effects.
 - Climate effects: The climate profile assumed in the SEER rating process is a poor match for most of the California climates. As a result, climate effects provide the largest source of bias in the reliability of rated SEER in California residential applications, approximately +10% to -20% or half to two-thirds of the total bias. Tabular correction factors were developed that were able to significantly reducing error in both SEER and EER, to approximately $\pm 6\%$ or 7%.
 - Building effects: The cooling load distribution and resulting mid-load temperature (82°F) assumed in the SEER rating process is poorly suited for California residential applications. As a result, building effects (i.e., typical variation found amongst California single-family residences) provide the second largest source of compromise in the reliability of rated SEER in California residential applications, approximately $\pm 7\%$, or one-fourth to one-fifth of the total bias.
 - System effects: One of the most fundamental assumptions implicit in the SEER process is that system efficiency varies linearly with outdoor condenser temperature. This study found that for residential applications, this is largely true, however, effects due to non-linearity in system sensitivity to condenser temperatures plus other system effects such as cycling degradation and lower wet-bulb for coil entering conditions combined to provide the third largest source of compromise in the reliability of rated SEER in California residential applications, approximately $\pm 5\%$, or one-one-fifth to one-sixth of the total bias. The impact of low wet-bulb entering coil conditions was not closely examined by this study and its impact is confounded with climate effects reported above.
- In non-residential applications in California, climate effects account for the smallest inaccuracy of the SEER and EER ratings. Significant sources of error in using SEER or EER in non-residential applications require additional investigation to more fully understand. The major sources of error include the following:
 - Building effects: Non-residential buildings tend to have much greater variation in internal

load and solar load, significantly compromising the implicit relation SEER assumes between cooling load and outdoor temperature.

- System effects: In non-residential buildings, public health codes require indoor fans to run continuously to provide needed ventilation during occupied hours; thus, indoor fan energy becomes a significant portion of the total HVAC system energy, especially in milder climates. The SEER rating process assumes the indoor fan cycles with the condensing unit compressor and fan.
- This study demonstrates that significant variation in annual cooling efficiency exists amongst equally rated cooling equipment (using only SEER as an indicator of cooling efficiency). In November of 2002, ARI decided to no longer include EER in its equipment performance listings of SEER-rated equipment. Having at least two ratings points, i.e., SEER and EER, is critical to the energy efficiency industry in California.

7.0 Next Steps

This research has demonstrated that individual differences between identically rated HVAC systems, combined with simplifications implicit in the SEER ratings process, can significantly compromise the ability of a SEER rating to be a reliable predictor of cooling system performance in California. While the research summarized here has done much to characterize the scope of the problem with SEER ratings and demonstrate effective climate based SEER corrections, much more needs to be done. The items below are suggested as important follow-on research.

- This work should be extended as follows.
 - Include systems rated as SEER 13 (the minimum efficiency for the 2005 standards);
 - Include additional high efficiency two-speed systems (SEER 15 and 18 ratings);
 - Add HVAC equipment penetration rates and apply statistical methods to more accurately characterize the California state-wide impacts of performance variability on expected savings and demand.
- More study is needed to explore how the inherent performance variability of SEER-rated HVAC systems, as characterized by this research, can be applied to:
 - the future development of the California energy efficiency standards to better ensure resultant savings;
 - utility incentive programs to improve efficiency realization rates.
- In residential applications, additional research is required to more effectively correct for:
 - building effects, e.g., varying mid-load temperatures;
 - system effects, e.g., especially off-rated coil entering conditions.
- In non-residential applications, additional research is required to better understand and characterize:
 - building effects due to
 - increased internal loads,
 - core/perimeter HVAC zoning,
 - and occupancy ventilation;
 - system effects due to
 - indoor fan energy and operation, and
 - off-rated coil entering conditions.

8.0 References

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Appendix A: EER and SEER Testing and Rating Process Details

The EER and SEER ratings require up to four laboratory tests. Two of the tests are required, one each for EER and SEER. The other two tests are optional and serve to determine C_D , a system's cycling degradation coefficient. If the two tests to determine C_D are not conducted, a default value for C_D is assigned ($C_D = 0.25$). Since the default value for C_D is not very flattering given typical designs for today's cooling systems, hence all four tests are commonly conducted. Table A.1 summarizes the tests and their conditions.

Table A.1 Summary of EER and SEER Test and Rating Requirements

			Mode of Operation	Outdoor Dry-Bulb Temperature	Outdoor Wet-Bulb Temperature	Indoor Dry-Bulb Temperature	Indoor Wet-Bulb Temperature
Test A	EER	required	steady state	95°F	75°F	80°F	67°F
Test B	SEER	required	steady state	82°F	65°F	80°F	67°F
Test C	C_D	optional ¹	steady state	82°F	65°F	80°F	57°F ²
Test D	C_D	optional ¹	cyclic (6 min. ON 24 min. OFF)	82°F	65°F	80°F	57°F ²

NOTES

1 If the two tests to determine C_D are not conducted, a default value for C_D is assigned ($C_D = 0.25$)

2 wet-bulb temperature should be sufficiently low that no condensate forms on the evaporator

EER is determined from equation A.1. SEER is determined from equation A.2.

$$EER = EER_A \quad (A.1)$$

where:

$$EER_A = \frac{\text{cooling capacity (Btu / h)}}{\text{power input (W)}} \text{ as determined by steady state test A (at 95°F)}$$

$$SEER = EER_B * (1 - 0.5 * C_D) \quad (A.1)$$

where:

$$EER_B = \frac{\text{cooling capacity (Btu / h)}}{\text{power input (W)}} \text{ as determined by steady state test B (at 82°F)}$$

$$C_D = \frac{1 - \left(\frac{EER_D}{EER_C} \right)}{1 - \left(\frac{\text{Cooling Capacity from Test D}}{\text{Cooling Capacity from Test C}} \right)} \text{ as determined by steady state test C and cycling test D, else, if tests C and D are not conducted, } C_D = 0.25$$

where:

$$\text{EER}_C = \frac{\text{cooling capacity (Btu / h)}}{\text{power input (W)}} \text{ as determined by steady state test C (at 82°F)}$$

$$\text{EER}_D = \frac{\text{cooling capacity (Btu / h)}}{\text{power input (W)}} \text{ as determined by cyclic test D (at 82°F)}$$