Peak Demand Impacts of Residential Air-Conditioning Conservation Measures

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The combination of electrical end-use metering data and computer simulations can be of great use in designing optimal demand side management (DSM) programs to reduce peak electrical demand from residential air conditioning systems. Preliminary results from an effort of this sort are presented here. The electrical end-use metering data analyzed is from 194 houses in the central valley of California. Up to 25% of the air conditioner units were topped out at the time of peak residential electrical demand. At the same time, over 20% of the air conditioners were off. Results from cooling season simulations of a typical ranch style house in Sacramento or Fresno are also presented. The effects of duct retrofits, multi-speed very high-SEER air conditioner units, and capacity reductions are explored. The reason for the simulations is that some potential DSM measures, such as installing air conditioning units which achieve high SEER ratings by using multiple speeds, might have little effect on peak demand. Other measures, such as duct retrofits, potentially have larger effects on peak demand than on seasonal energy use. The most striking result of the simulations was the contrast between very-high SEER units and downsized a/c units. The very high-SEER units decreased seasonal energy use but had no effect on peak electrical demand. The downsized units had no effect on seasonal energy use but lowered peak electrical demand.

Introduction

Residential air conditioning (a/c) has a disproportionately large impact on peak electricity demand in California because it represents a large connected demand which most households use for relatively few hours each year (EPRI 1992). The effects of residential cooling demand side management (DSM) programs on peak demand are potentially large and merit careful examination.

Studies by electrical utilities (ibid.) have concluded that DSM programs are important for both system and local peak demand. Reductions in local peak demand could allow utilities to delay transmission and distribution (T&D) upgrades (ibid.). An example is the Delta Project of Pacific Gas and Electric Company (PG&E), where savings valued at $35 million dollars over 30 years are projected to result from DSM programs to reduce local and system peak (ibid.).

Since residential air conditioning is considered to represent a large fraction, up to 90% (Hull and Reddy 1990), of residential electrical demand during days of peak system demand, there has been much research on estimating its effect on peak residential system demand (e.g., ibid.). The two factors which are thought to be most important in determining demand during peak days are the air conditioner electrical draw and the behavior of the occupant (EPRI 1992; Reddy and Claridge 1993).

The effects of cooling system conservation measures on annual and seasonal energy use are obvious. Sealing and insulating ducts will reduce annual cooling energy use by reducing conduction and leakage losses from ducts. Sealing duct systems will also cut infiltration losses caused by uneven supply and return flows. Installing a/c units with very high Seasonal Energy Efficiency Ratios (SEER) will reduce annual energy use although not necessarily in exact proportion to SEER. For peak demand, the effects of these “improvements” are not so obvious. If the air conditioner is undersized, the efficiency improvement from sealing and insulating ducts may result in improved occupant comfort on peak demand days rather than a lower electrical demand. If the measures which manufacturers take to increase SEER (e.g., variable speed drives) don’t improve the air conditioner efficiency under peak conditions then there will be no effect on peak demand. In contrast, some measures may have larger effects on peak demand than on seasonal energy use. If the air conditioning unit was properly sized, then sealing and insulating ducts results in larger fractional changes in peak electrical demand (Modera and Jansky 1994).

According to EPRI (1992) and Reddy and Claridge (1993), an effective DSM program for reducing peak electrical demand from residential air conditioning must reduce the connected demand. It is possible to decrease connected load and improve occupant comfort, if a/c unit downsizing is accompanied by appropriate improvements to the duct system. The strategy for a customer with sufficient cooling capacity would be to downsize their unit to offset improvements in duct efficiency. For a customer with insufficient cooling capacity, the unit would still be downsized, but by a smaller percentage than the improvements in duct efficiency during the time of peak electrical demand. This strategy will reduce peak demand for all customers while also improving occupant comfort.

It is thought that reducing the capacity of air conditioning units will benefit occupant comfort in regions where humidity control is an important function of air conditioning (Hull and Reddy 1990). A small unit running for more time is more effective at extracting moisture from the air than a larger unit which is cycling. If the system was oversized, putting in a smaller capacity unit could also improve the a/c unit efficiency by reducing cycling losses.

Computer simulations are an appropriate way to estimate the effects of duct system and a/c equipment changes. A detailed simulation tool is necessary because of the complex interactions between quantities such as the duct system efficiency, a/c equipment efficiency, envelope infiltration losses, and envelope thermal masses. A detailed explanation of these interactions is given in Modera and Jansky (1992).

An existing simulation system for building energy use (Modera and Jansky 1992) has been modified to accurately model heat storm conditions. Air conditioning modelling has been improved by using manufacturers' data on capacity and power draw for common high and very high efficiency units. Seasonal simulations were performed on a typical ranch style house in a central valley location. The effects of very high SEER units, unit oversizing, thermostat control strategies, duct insulation, and duct sealing were investigated. The implications of these results for peak and seasonal energy demand are assessed.

One element of energy use which has not been dealt with deeply in other simulation programs is the interaction between DSM measures and the two important points cited by other researchers, the degree of oversizing in the a/c population and occupant behavior. To quantify the degree of oversizing in the population of a/c units, we have analyzed hourly data on air conditioner and household electrical draw for 194 houses from PG&E's Appliance Metering Project (AMP). In particular we have quantified the air conditioner usage by this set of houses on the day of peak system demand for PG&E. We also estimate unit oversizing from the pattern of air conditioner demand. Future work will extend this analysis and also consider dividing the houses into groups according to their occupant behavior.

Analysis of Air Conditioner and Household Electrical Use Data

We have analyzed a portion of the end-use metered data from PG&E's Appliance Metering Project (AMP). The data is described in Eto and Moezzi (1992) and consists of hourly averages of end-use metered electrical data from over 700 of PG&E's customers. In our analysis, we have only considered the total household demand and the air conditioning demand.

The AMP data covers the years 1985 through 1989. In this paper we present results from the data for 1989. The data covers many climate zones, but we have restricted ourselves to 2 climate zones in the central valley of California. Climate zones 2 and 3 are centered on the cities of Sacramento and Fresno, respectively. End-use metering was done on 194 houses in these two zones. We will use the names Sacramento and Fresno below to indicate climate regions 2 and 3, respectively.

In 1989, the peak systems electrical demand for PG&E occurred on July 19th at 4 pm (Woodrow Whitlatch, PG&E, personal correspondence). The maximum temperature in Sacramento that day was 103 'F.

We can determine when the peak electrical demand occurs for the AMP houses in Sacramento and Fresno from the data. Relevant data about the electrical demand of houses at their peak and at the system peak are given in Table 1. The peak electrical demand for the houses, which we will call the residential peak, is on the same day as the system peak for Sacramento and one day earlier for Fresno. However, the time of the residential peak is later than the time for the system peak. Other researchers have noted the early evening peak in residential electrical demand (e.g., EPRI 1992). We will use the simulation results below to explain why the peak electrical demand occurs in the early evening.

Another point to note in Table 1 is the high fraction of the household electrical demand which is due to air conditioning equipment. At the system and residential peaks, over 60% and 70%, respectively, of the average household demand is due to air conditioning. This is more impressive when you note that 25-30% of the air conditioners are off at the time of the system peak and 20% are off at the residential peak. This is an important point. At the

Table 1. Results of Analysis of Monitored Electrical Draw Data for the Set of Houses at Their Peak Electrical Demand and at the Peak System Electrical Demand

	Quantity	Value Region 2 (Sacramento)	Region 3 (Fresno)
Peak Household Electrical Demand	date	7/19/89	7/18/89
	time	5-6 pm	6-7 pm
	kW/house	4.2	4.6
	% of demand from air conditioning	71	65
	% of air conditioners on	77	79
Household Electric Demand at System Peak (July 19, 1989 at 4 pm)	kW/house	2.9	3.4
	% of residential demand due to air conditioning	66	61
	fraction of air conditioners on	75	69

annual system and residential peaks, a large fraction of the air conditioners in these climates are not on.

Now that we know the electrical demands of the sample houses at the system and residential peaks, we should consider how demand varies during the system peak day. Figure 1 shows the variation of air conditioning demand for each region as a function of time for the day of the peak system demand. The two regions have similar profiles. Air conditioning electrical demand climbs steadily from 8 a.m. until its peak in the early evening and then decreases until 6 a.m.

Figure 2 shows the fraction of air conditioners turned "on" for the two regions during the day of peak system demand. "on" is defined as having a cooling electrical demand greater than five percent of the maximum cooling electrical demand experienced during the summer. The most important thing to note is that at no time are more than 80% of the air conditioners on. At the time of the system peak, over 30% of the systems are off.

We do not have access to the air conditioning equipment power ratings for the houses, but we can estimate the maximum air conditioner draw by finding the maximum of the hourly averaged air conditioner electrical demands during the summer for each house. Unless the unit is severely oversized or was used very little, this is a good estimate of the maximum possible draw. We excluded houses where this maximum was below 1.5 kwh since this is less power than any common central air conditioners

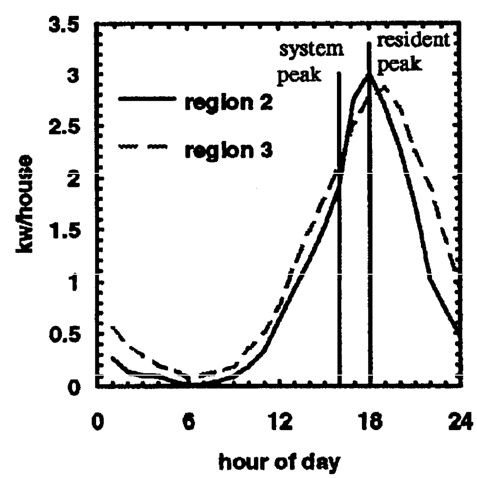

Figure 1. Air Conditioning Demand as a Function of Time for the Day of Peak System Demand. Note the different times for system peak and household air conditioner demand peak.

use if it is on continuously. It should be emphasized that the maximum draw is a function of outside temperature and it is observed to vary by up to 15% with time of day. Figure 3 shows a histogram of maximum air conditioner electrical demands for the houses in regions 2 and 3. The mean value is 4.6 kwh with a standard deviation of 1.8 kwh.

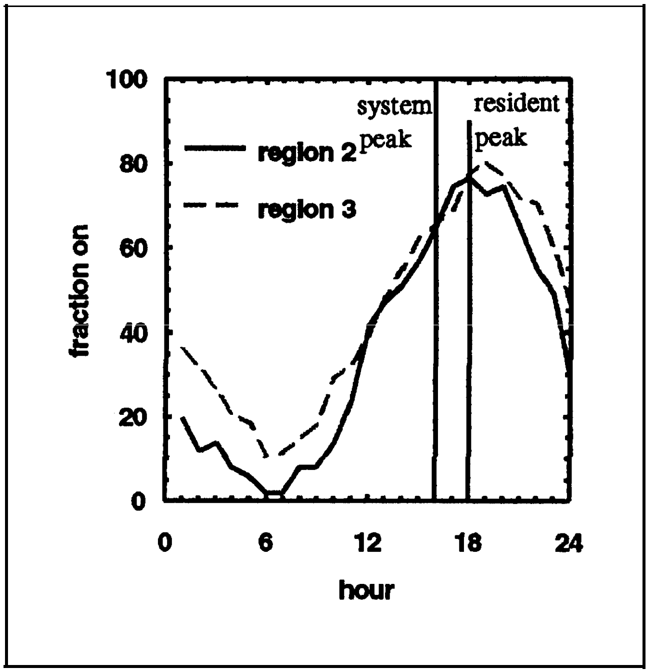

Figure 2. Fraction of the Sample of Residential Air Conditioning Units Which Are on as a Function of Time on the Day of Peak System Demand

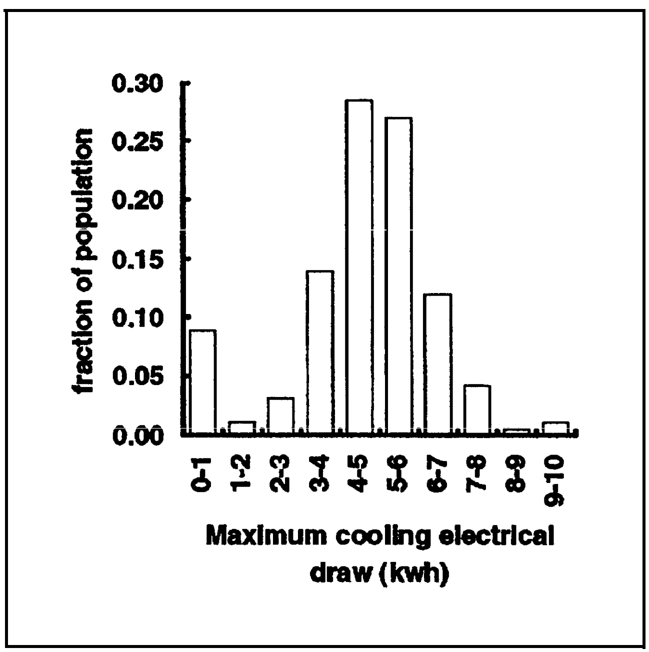

Figure 3. Distribution of the Maximum Cooling Electrical Draw for the Sample Set of Houses in Regions 2 and 3. The average and standard deviation are 4.57 and 1.84 kwh, respectively.

One factor which is of interest is how many of the air conditioning units are topped out at the system and residential peaks. We can estimate this by using the maximum air conditioner demands from Figure 4. Figure 4 shows the fraction of houses with air conditioning electrical demands within 15%, 5% and 0% of their maximum demand for the cooling season during the system peak day. At the system peak, 5% and 8% of the air conditioners in Sacramento and Fresno, respectively, are within 5% of their maximum electrical draw. Only 2-3% of the air conditioners are at their maximum draw during the system peak. Note that 'the unit electrical draw depends on the outside temperature, which means that the maximum electrical draw will vary with the severity of the weather. The fraction of a/c units with electrical demand within 5% of their maximum is a reasonable upper limit for the fraction of homes topped out. It is reasonable because the weather at the system peak is severe, so air conditioners that are on continuously will draw near their maximum current. It is an upper limit because some of the units are so oversized that they never top out. Using the criteria, we estimate that no more than 8% and 12% of the houses in Sacramento and Fresno are topped out at the system peak, respectively. At the residential peak, no more than 25-30% of the houses are topped out in either region.

The average fraction of capacity used during the system and residential peaks is also of interest. Again we can use the maximum draw for each house during the cooling season as an estimate for the maximum possible draw. At the system and residential peaks, average fractions of maximum draw for the houses were 40% and 60%, respectively. Although all of the systems did at some time use their "maximum draw" by definition, this implies there may be a large potential for downsizing air conditioning equipment without sacrificing occupant comfort. It should be noted that some of the air conditioners are not topped out at their maximum electrical demand.

There are several important points we have found in analyzing the AMP data. Air conditioner electric draw is approximately 65% of the total electrical draw of the houses during the system peak hour, even though 25-30% of the households are not using their air conditioners at that time, Up to 25% of the houses have air conditioners which are topped out during the residential peak. All of these results will have impacts on the effectiveness of DSM programs.

Simulation Results

The eventual goal of this project is to integrate the analysis of the AMP data with computer simulations to design optimal DSM programs for duct retrofits and air conditioner unit replacement which will reduce local and system peak demand while improving occupant comfort. As an early step towards this result, we have performed cooling season simulations on a prototype house for which various combinations of duct improvements and system resizing have been applied to a base case.

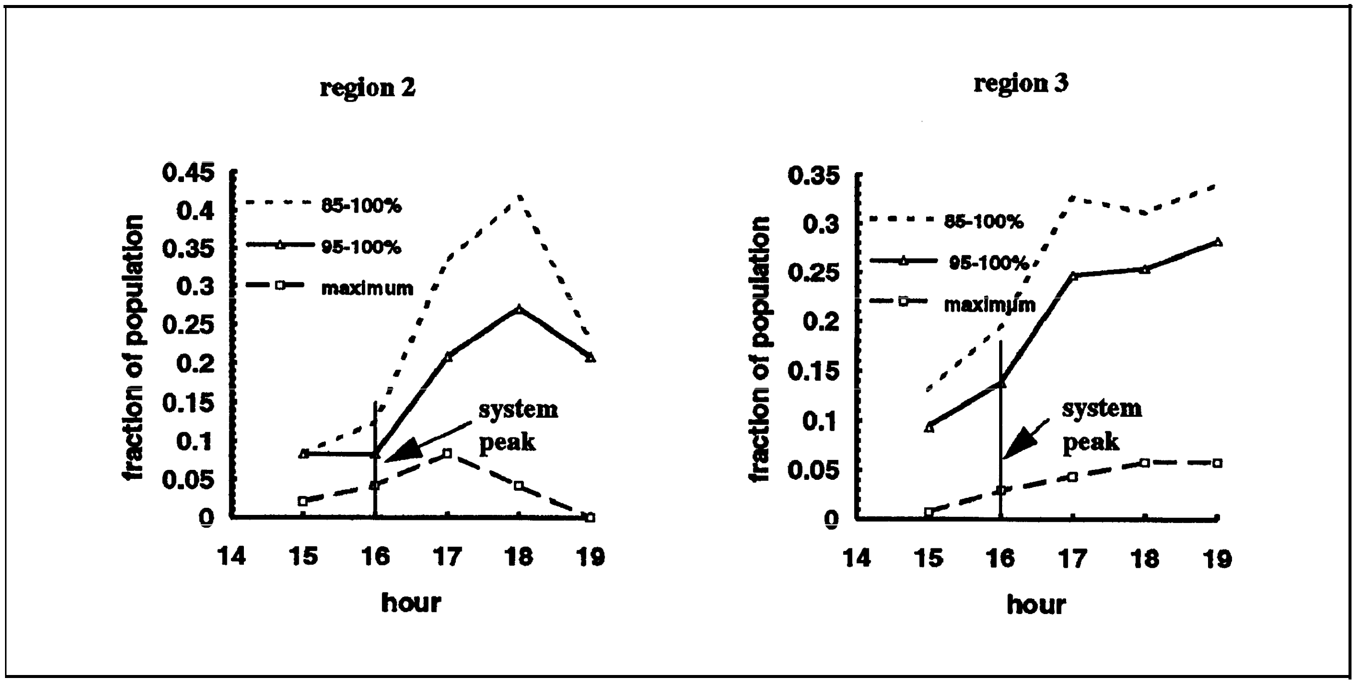

Figure 4. Fraction of the Residential Air Conditioning Units in the Sample Set of Houses Which Are Near Their Maximum Demand as a Function of Time on the Day of Peak System Demand

Several researchers (see EPRI 1992 and Reddy and Claridge 1993) have stated that it is necessary to reduce the connected demand in order to be effective in decreasing peak electrical demand. Without downsizing the air conditioner's electrical draw, occupant behavior and/or preferences may overcome any increases in efficiency. One assumption behind this conclusion is that many air conditioning units are insufficiently sized for peak days, i.e. they "top out, and improvements in duct efficiency will be taken back in improved occupant comfort. We found above that up to 25% of the household air conditioners were topped out at the residential peak. For houses which have adequately sized or oversized air conditioners, it is occupant behavior which affects peak demand. A person who returns from work and turns on the air conditioner after the house has been heated all day will produce a large demand for several hours. Reducing the connected demand for persons exhibiting this behavior will be effective in reducing peak demand, although at a cost in customer comfort unless other improvements are made.

Our prototype house was chosen with envelope leakage area, insulation levels and construction type which are typical of homes constructed in California prior to Title-24. The same specifications were used by Modera and Jansky (1992) and are described in Table 2. Three duct systems were chosen for the house and are described in Table 4. The "standard" duct system is typical for California and its leakage is described in Table 5. Duct systems 2 and 3 represent improvements in insulation and sealing, respectively. Duct system 4 combines the improvements of systems 2 and 3.

Table 2. Characteristics of the House

House	Single Story Ranch
Foundation	crawlspace
Floor Area	144 m^2 (1540 ft^2)
Basement, Interior Wall, and Floor Insulation	none
Ceiling Insulation	R-11
Exterior Wall Insulation	none
Windows	single pane
Envelope Leakage Area	860 cm^2 (6 cm^2/m^2 of floor area)
Basement/crawlspace Leakage Area	75 cm^2
HVAC System Location	garage
Duct System Location	attic and garage
HVAC System Operation	Cooling setpoint 26°C (78°F) No opening of windows

Table 3 describes the four units simulated in this study. An emphasis has been placed in this paper on comparing high and very high-SEER air conditioning units with

Table 3. Hypothetical Air Conditioning Equipment for the Crawlspace House

Name	Type	Capacity	Fan Flow	Fan Power (watts)	SEER	COP(a) Low Output(c)	COP(a) High Output(d)	COP(b) Low Output(c)	COP(b) High Output(d)
A	single speed	10.5 kW (36 kBtu/hr)	2040 m^3/hr (1200 cfm)	550	12	2.9	2.9	3.4	3.4
B	two speed	5.3 kW low (18 kBtu/hr) 10.5 kW high (36 kBtu/hr)	1020 m^3/hr (600 cfm) 2040 m^3/hr (1200 cfm)	80 low 550 high	16	4.5	2.9	4.8	3.4
C(e)	single speed	8.75 kW (30 kBtu/hr)	1700 m^3/hr (1000 cfm)	460	12	2.9	2.9	3.4	3.4

(a)Includes indoor fan power.
(b)Does not include indoor fan power.
(c)5.3 kW, for single speed units this requires cycling.
(d)10.5 kW.
(e)This is unit A, downsized by 20%.

Table 4. Duct Systems Used in the Crawlspace House

Property	Duct System 1	2	3	4
Construction Type	flex duct			
Leakage Level (% of standard)	100%	100%	20%	
Insulation Level	R-4	R-8	R-4	R-8

Table 5. Distribution of Duct Leakage in Crawlspace House

ELA Type (cm^2@ 4 Pa)	Supply Duct ELA	Return Duct ELA
To attic	59	38
To garage	10	38
Total	69	78

SEER ratings of approximately 12 and 15, respectively. The SEER ratings are approximate because we specify coefficients of performance (COP) in the simulation program input, not SEER ratings. The characteristics of the units were chosen by examining the specifications of high and very high-SEER units from several manufacturers. To aid comparison, Unit A, the single-speed high SEER unit, is identical to Unit B operating at high capacity. The capacity of Unit A was chosen to nearly meet the maximum load during the peak hour for the house. Unit C, the downsized unit, has the same efficiency as Unit A to aid comparison.

The reason for emphasizing two-speed air conditioners is to point out that they will not reduce peak demand relative to efficient single speed units. This is because very high-SEER units, when running at high capacity, are very similar to high-SEER units. During times of peak demand, most high-SEER units will be ruining at their high capacity setting. It is the COP of the air conditioner at high capacity and its performance in extreme temperatures which are important for peak electrical demand. This is true for multi-speed units which are not drastically oversized, i.e. units which are operated at their high capacity setting.

One important question for annual energy use of two-speed air conditioners is how they are operated when the cooling load is between the low and high cooling capacities. One extreme case, which we will denote as control strategy i, would be for the unit to cycle at high capacity whenever the low capacity does not meet the cooling requirements. The opposite extreme, denoted here as strategy ii, would be for the unit to be on continuously whenever the cooling load is not met at low capacity. Results are presented for both control strategies in order to bracket the possible results.

The results from the simulations are summarized in Tables 6 and 7. In both tables, the peak electrical demand is referred to. This peak electrical demand in the simulations occurred on July 11th from 3-4 pm. For the base case, the a/c unit is topped out from 3-7 pm on July 11 and the peak electrical draw occurs at 3 pm because that is the hottest hour of the day when the unit is topped out. The peak day does not correspond to the utility peak because we used typical meteorological year (TMY) weather data. For reference, the peak temperature in our weather data was 104°F on July 1lth at 3 pm. The attic, where most of the ducts are located, was simulated to have a temperature of 116°F at that time.

From the output of the cooling load that is required, but not met, for the simulated house, we see that the maximum cooling is required from 5-6 pm on the peak day. This peak occurs in the early evening, rather than the afternoon, because of the time constant of the thermal mass of the building. It is not necessarily a consequence of occupant behavior, although the peak could be made more extreme by occupant behavior, e.g., coming home from work in the afternoon and turning on the a/c.

Table 6 summarizes the effects of duct system retrofits and equipment resizing on seasonal and peak energy use. For Unit A, insulating ducts to R-8 or sealing 80% of their leakage produces savings in seasonal energy use of 6% and 8%, respectively. However, for peak electrical demand there was no change because the system is topped out during the peak hour for all three duct systems simulated. Unit B, with either control strategy, gives large savings in seasonal energy use but also fails to reduce peak demand because the system is topped out at high capacity during the peak hour.

Only when using Unit C, the downsized unit, is there a reduction in peak electrical demand. However, Unit C shows little or no savings in seasonal energy use relative to Unit A. Since Unit C has a lower capacity and therefore has fewer cycling losses, you might expect a lower seasonal energy use. This would be the case if the air conditioner were attached to a perfect duct system. However, the duct system is not perfect and its efficiency decreases with the capacity of the a/c unit. This is because a smaller fan is used with the downsized unit which means the conditioned air is in the duct system for more time

Table 6. Changes in Energy Consumption Relative to the Base Case

Unit/Control Type	Case: Cooling Capacity (% of base case)	Case: Leakage (% of base case)	Case: Insulation (R-value)	Percentage Change in Energy Consumption Relative to the Base Case: Season	Peak	*savings $_{peak}$/ savings $_{season}$*
a	100	100	4[(a)]	0	0	0.00
			8	6	0	0.00
		20	4	8	0	0.00
b, strategy i	100	100	4	14	0	0.00
			8	22	0	0.00
		20	4	21	0	0.00
b, strategy ii	100	100	4	21	0	0.00
			8	32	0	0.00
		20	4	28	0	0.00
c	100	100	4	0	17	undefined
			8	8	17	2.1
		20	4	8	17	2.1
			8	15	17	1.1

(a) Base case

Table 7. Changes in Energy Consumption, Effective Capacity, and Occupant Comfort Relative to the Base Case During the Peak Hour

Unit/Control Type	Case Cooling Capacity (% of base case)	Leakage (% of base case)	Insulation (R-value)	Changes During Peak Hour Relative to the Base Case: Electrical Demand	Effective Capacity[(a)]	Occupant Comfort
a	100	100	4[(b)]	0	1.00	-
			8	0	1.10	improved
		20	4	0	1.18	improved
b, strategy i	100	100	4	0	1.00	unchanged
			8	0	1.10	improved
		20	4	0	1.18	improved
b, strategy ii	100	100	4	0	1.00	unchanged
			8	0	1.10	improved
		20	4	0	1.18	improved
c	100	100	4	17	0.80	worsened
			8	17	0.92	worsened
		20	4	17	0.93	worsened
			8	17	1.05	improved

(a) Effective capacity - (unit capacity)*(duct system efficiency)
(a) Base case

after leaving the cooling coil. This allows the air to lose more energy by conduction through the duct walls. The smaller fan speed should also reduce leakage losses. The decreased cycling, decreased leakage, and increased conduction losses nearly offset each other for this particular house. The greater effect of duct insulation on Unit C, relative to Unit A, is consistent with this explanation.

The most interesting point to draw from Table 6 is that reductions in peak and seasonal electrical use are not at all correlated. The two-speed a/c unit produces large savings in seasonal energy use but has no effect on peak demand. In contrast, the downsized unit produces little or no savings in seasonal energy but reduces peak demand by 17%. Obviously, this must be taken into account when designing air conditioning DSM programs for homes which do not have oversized air conditioning systems. From the analysis of the sub-metered data, this seems to apply to approximately one quarter of the housing stock in the central valley of California.

The results in Table 6 reinforce the conclusion that residential air conditioning DSM programs must reduce connected demand in order to provide substantial benefits in the case of an air conditioning system that is topping out during the peak demand hours. Only the reduced capacity unit lowered electrical demand during the peak hour. However, Table 7 does not contain any results for the effects of system retrofits on occupant comfort on peak days. This is reflected in the effective capacity of an HVAC system.

The effective capacity of an HVAC system is the rate of energy delivery to the conditioned space. This is the product of the air conditioner capacity and the efficiency of the duct system. In Table 7 we present the ratio of the effective capacity of the HVAC system to that for the base case.

If the air conditioner in a house tops out on peak days, any improvement in the effective air conditioning capacity will improve occupant comfort. We have noted in Table 7 which combinations improved or worsened occupant comfort. In only one case was the occupant comfort improved and the peak demand reduced. This is for HVAC Unit C using the duct system which was both sealed and insulated. When only the duct system was retrofitted, the occupant comfort was improved but their was no improvement in peak demand. When only the air conditioning unit was retrofitted, occupant comfort worsened and peak electrical demand decreased.

The results presented here are relevant to the fraction of the housing population which has air conditioning systems that have insufficient capacity to meet cooling loads during peak demand hours. It was shown above that this is a significant fraction of the sample of houses considered here.

Summary and Conclusions

Results have been presented in this paper from a project to evaluate the effects of air conditioning equipment and duct system retrofits on local and system peak electrical demand. The objective of the project is to design optimal DSM programs for reducing peak electrical demand while improving occupant comfort. The most important factors in determining the effect of residential air conditioners on peak electrical demand are system oversizing and occupant behavior (Reddy and Claridge 1993). Consequently, our analysis of the field data from 200 houses in the central valley of California concentrated on determining the degree of system oversizing and the fraction of air conditioning units which are turned on.

The first notable result from the analysis of the field data, which is confirmed in other research (Hull and Reddy 1990), is that significant fractions of the set of air conditioners monitored are not operating during peak periods. At the system and residential peaks, 25-30% and 20% of the air conditioners were not operating. It was also found that the percentage of air conditioners topped out was no more than 8-12% and 25% at the system and residential peaks, respectively.

Computer simulations were performed for a ranch style house in Sacramento, California with a slightly undersized air conditioning system. Various combinations of sealing the duct system, insulating the duct system, replacing the a. c. unit with a two-speed high-SEER unit, and downsizing the a.c. unit were simulated. It was found that the only way to reduce peak electrical demand in this case was to downsize the unit. Since the air conditioner was undersized, duct improvements alone resulted only in improvements in occupant comfort. A combination of downsizing the a.c. unit and improving the duct system was required to both reduce peak demand and improve occupant comfort.

The most striking result of the simulations was the contrast between the effects of using high-SEER units which were not downsized, or downsizing the a.c. unit and maintaining the same efficiency. The two-speed units gave large reductions in seasonal energy use but had no effect on peak demand. The downsized unit had little or no effect on seasonal energy use but lowered peak demand. In comparing air conditioning units for DSM programs to reduce peak demand, it is the performance of a unit at its highest capacity during extreme temperature periods which is important, not a high SEER rating. A more useful measure than SEER for peak demand is the unit performance at outdoor temperatures of 95°F or higher. This data is already provided by manufacturers of air conditioners.

Future work on this project will include further analysis of the sub-metered data in order to determine more about the effects occupant behavior. We will attempt to group the houses into several behavior types, perhaps using methods similar to Hull and Reddy (1990). In addition, more sophisticated methods will be used to determine the maximum a/c unit draw and the fraction of the sample houses which is topped out. For simulation work, the addition of real weather data and performing simulations with air conditioning units that are oversized will help in the design of optimal DSM programs for residential air conditioning.

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