Are Smart Homes More Efficient? Energy Impact of California's Residential Automated Demand Response Program

Katherine Wang, Rocky Mountain Institute
Joel Swisher, Rocky Mountain Institute

ABSTRACT

This paper reviews the technical performance of the Automated Demand Response System (ADRS) pilot program conducted jointly by three major utilities in California. Summer 2005 is the second year of the pilot's operation using GoodWatts, an advanced, two-way, real-time, comprehensive home energy management system. The continuation of the ADRS pilot into 2005 as directed by the California Public Utilities Commission was intended to allow a comparison of summer 2004 with summer 2005 to evaluate persistence and learning of ADRS technology.

Customers with ADRS technology and subject to dynamic, critical peak pricing rates in the inland (hot) climate zone successfully achieved load reductions compared to control customers without ADRS technology on standard tiered rates. The load reductions were substantial and stable across a range of days and temperatures. Technology appears to be an important driver in reducing load, especially peak period load, for high-consumption stratum homes (i.e. homes with summer average daily usage greater than 24 kWh).

Introduction

On October 29, 2004 the *Assigned Commissioner and Administrative Law Judge's Ruling Continuing Availability of Tariffs and Programs Under the Statewide Pricing Pilot* (SPP) directed the joint utilities of Pacific Gas & Electric (PG&E), Southern California Edison (SCE), and San Diego Gas & Electric (SDG&E) to file tariffs to allow the critical peak pricing tariff options to be extended to December 31, 2006 and to continue the Advanced Demand Response System (ADRS) through December 31, 2005. The objectives of the program extension as defined by the ruling are:

1. Estimate the average ADRS residential customer's load response to the ongoing CPP-F, Ratio A tariff from July of 2004 to September of 2005.
2. Evaluate whether the level of load impacts of ADRS residential participants in response to CPP price signals has increased, decreased or stayed the same over time after controlling for weather and other independent factors, including a comparison of load impacts/response levels observed in summer of 2004 to levels observed in the summer of 2005.
3. Evaluate whether customer satisfaction levels (and perhaps willingness to pay for these systems) have increased or decreased over the course of the pilot.

Rocky Mountain Institute (RMI) was tasked to fulfill the ADRS research objectives 1 and 2, and is covered in this report. The third objective, evaluate whether customer satisfaction levels have increased or decreased over the course of the pilot, was tasked to a second evaluator in a separate report.

This report thus compares the load reduction impact of the summer 2004 pilot with the summer 2005 pilot. Results are presented for each utility separately and a statewide weighted average load impact. Particular emphasis is placed on the results of high consumption stratum homes.

ADRS Pilot Design

The ADRS pilot participants were first recruited in 2004 from owner-occupied, single-family homes from the SPP climate zone 3 (hot inland) in zip codes served by appropriate television cable providers who agreed to cooperate in the pilot program[1]. ADRS homes were recruited at random regardless of historical consumption, although homes were screened for eligibility with respect to presence of central air conditioning (AC), within the prescribed zip codes. Because ADRS technology is capable of controlling end uses in the home in addition to central air conditioning, homes were screened for availability of other loads (i.e., swimming pool pumps and spas), but not disqualified from participation in their absence.

The homes used for the 2005 analysis consisted of those households that remained on the ADRS pilot program after the summer of 2004. The ADRS program was offered to incoming residents of existing ADRS homes, in the event of rental or sale situations. However, no additional participant homes were recruited for the 2005 pilot extension.

A total of 175 homes were initially recruited into the ADRS pilot program in 2004, consisting of 75 homes from PG&E, 76 homes from SCE, and 24 homes from SDG&E. However, by the start of the second year of the pilot in July 2005, a number of participants opted out of the program, and only 131 homes remained. A set of 154 control homes was also identified from which the ADRS participant reductions were measured consisting of 35 from PG&E, 58 homes from SCE, and 25 from SDG&E. These homes were on standard tiered rates and did not possess GoodWatts, but matched the ADRS participants in that they were also owner-occupied, single family homes from the SPP climate zone 3 with central AC. All homes were segmented into two strata based on summer average daily energy consumption (ADU). Home were classified as high consumption if their summer ADU was 24 kWh or greater and were classified as low consumption homes if less.

ADRS participants were placed on a time dependent electric rate schedule called CPP-F. The CPP-F electric rate is a time-of-use (ToU) tariff, which includes a critical peak pricing (CPP) element. Prices were higher between 2 p.m. and 7 p.m. ("peak period") every weekday ("non-event" days). Critical peak prices were imposed during the "Super Peak" period on a maximum of 15 days ("event" days) between July and September. All other hours, weekends and holidays were on the base rate ("off-peak" period). On the day of the Super Peak event, customers were billed at a price that was three times higher than the normal on-peak price. ADRS customers were notified by phone the day ahead of a Super Peak event during which the CPP rate element would be imposed.

In 2004, twelve Super Peak events were called. Four events were called in July, five in August, and three September. In 2005, eleven Super Peak events were called. Four events were

[1]Cusomer recruitment was concentrated to certain zip codes. ADRS homes were recruited in Woodland and Stockton (PG&E), Valencia, Santa Clarita, Saugus, and Los Angeles (SCE), and San Diego (SDG&E). These areas also correspond to Title 24 climate zone designations: 6 (SCE), 9 (SCE), 10 (SCE and SDG&E), and 12.(PG&E).

called in July, one in August, two in September, and five in October. Additionally, a number of Super Peak events were called on no more than three consecutive days in both 2004 and 2005, to examine the relative persistence of load reductions using technology.

ADRS Technology Description

One of the defining characteristics of California's ADRS program is the use of a residential-scale, automated demand response technology for a customer along with a dynamic pricing tariff. ADRS participants had the GoodWatts system, an Invensys Climate Controls product, installed in their homes. GoodWatts is an "always on", two-way communicating, advanced home climate control system with web-based programming of user preferences for control of home appliances. Via the Internet, homeowners with GoodWatts can set climate control and pool or spa pump runtime preferences and view these settings at any time both locally and remotely. Participants can also view whole-house or end-use specific demand in real time and display trends in historical consumption. The energy management technology includes the following components:

- Wireless RF communications network connecting all system components
- Two-way communicating whole-house meter capable of recording consumption data in 15-minute intervals
- Wireless Internet gateway and cable modem
- Programmable smart thermostats
- Load control and monitoring (LCM) device to manage selected loads (e.g., pool pump)
- Web-enabled user interface and data management software

GoodWatts allows users to view at all times the current electricity price on-line or via the thermostat. It has the further capability of allowing users to program desired thermostat and pool/spa responses to changes in electricity prices. For ADRS homes with pools and spas, supplemental LCMs were installed to garner additional demand reduction during utility triggered curtailment events.

Pilot Analysis Methodology

The three utilities provided 15-minute interval load data for ADRS and control homes for the period June 1 through September 31 for both years. Hourly temperature data were collected for the same periods, by zip code based on Invensys' weather subscription service. For each utility, average kW load for each interval was calculated by consumption stratum, for event and non-event days. The values were then used to construct daily average load curves for ADRS and control homes.

The average ADRS daily loads were then adjusted for self-selection bias based on summer 2004 weekends data. This was done following confirmation of the hypothesis that selection bias existed among ADRS customers, because they volunteered to participate, or selected themselves into, the program. The ADRS self-selection bias analysis was actually conducted using the combined evaluation of pretreatment data, summer 2004 weekends data, summer 2003 monthly billing usage data, and a qualitative review of marketing and recruiting materials. This was done because it was not possible to use true pretreatment data alone to detect and measure bias. The quality of the 15-minute interval pretreatment data was problematic, because they were collected for participants only after they signed up for the program, and the quantity of this data before July 1, 2004 was extremely thin. While all four data sources produced consistent results, summer 2004 weekends data was ultimately selected for the adjustment because it was a more robust data set and customers were charged off-peak rates, which we used as a proxy for pre-pilot program standard rates. Separate bias adjustments were calculated for each utility by consumption stratum, for event and non-event days, based on the differences in load between ADRS and corresponding control homes. The difference adjustments were small, between 0.3-0.6 kW on average between 2 p.m. and 7 p.m.

ADRS load savings, compared to the control group, were calculated for each 15-minute period by subtracting the adjusted average ADRS load from the corresponding average control home load, for each 15-minute data interval. ADRS load reductions relative to the control group were calculated for event and non-event days, by utility and by consumption stratum. A statewide average was calculated from the weighted average of the utility results.

Ninety percent confidence intervals for each 15-minute interval were also calculated for the average daily load curves. The intervals signify that we are ninety percent confident that the actual average load of homes in the general population (single family, with central air conditioning, in climate zone 3) are within the range of average load calculated for the sample. By calculating confidence intervals for both ADRS and control homes we also hoped to show that mean differences in load consumption were statistically significant. This was indicated if the confidence intervals above and below the two load curves do not overlap across the peak period.

Load Impact Results, 2004 and 2005 Pilot Years

Table 1 and Table 2 compare the 2005 and 2004 load reduction of high consumption ADRS customers against control homes on event and non-event days statewide. In general, high consumption ADRS load reduction was greater in 2004 than 2005, by 25% on average on event days and by 15% on non-event days, statewide.

The smaller load reduction on event days in 2005 is attributed mostly to lower control home loads in 2005, rather than reduced ADRS performance. Average Super Peak Period control home consumption in 2005 decreased by 8% compared to 2004, in spite of the fact that 2005 was estimated to be a hotter summer on average during the six summer months of the study. The lower average control home load in 2005 on event days is counterintuitive, and we cannot explain this difference in behavior with available data[2].

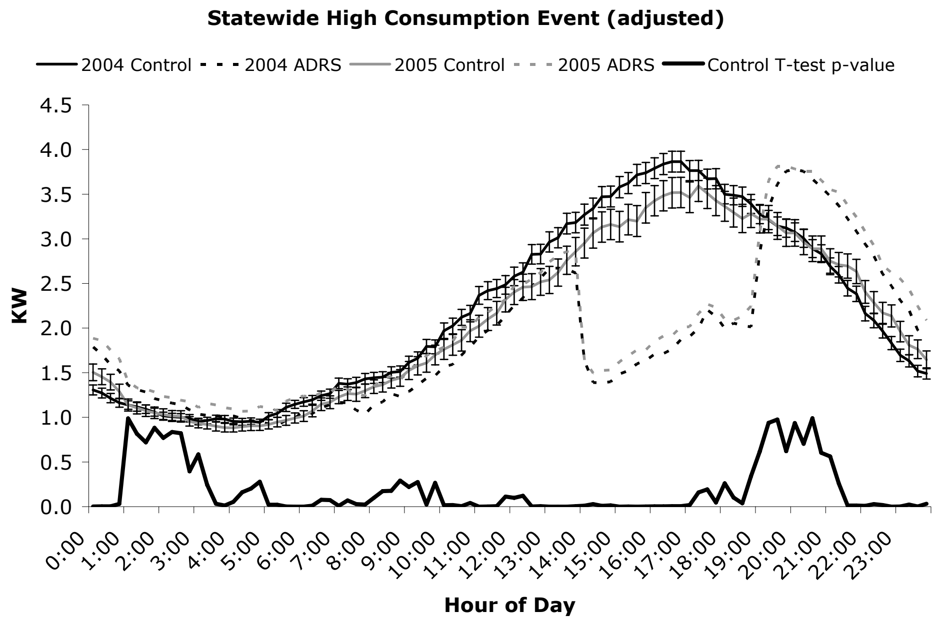
High consumption ADRS loads, on the other hand, increased by 7% during Super Peak periods on average in 2005, as expected during months with more cooling degree days. Note that the percent increase in ADRS Super Peak period load is calculated from a lower overall peak period consumption compared to higher control customer loads.

For both summers in Figure 1, note the rebound in home energy use during the two hours immediately following the Super Peak periods, from 7 p.m. to 9 p.m. At the end of the Super

[2]Household level investigation into control home consumption revealed a significant number of outliers, where control homes exhibited almost no consumption throughout the entire day. These high consumption control homes were removed from the sample for the 2005 analysis. The number of control homes removed did not reduce the statistical significance of 2005 results. Details of control home household-level analysis and removal of outliers are included in Appendix A, Data development and Methodology.

Peak period, the thermostats in ADRS homes automatically reset from their warmer Super Peak setting to their cooler off-peak setting. This results in an increase in off-peak energy use as the air conditioners start operating to meet the new, cooler set point, even on non-event weekdays. Peak period behavior of ADRS homes on non-event days are not shown here, but is similar to event day behavior.

Figure 1. 2005 and 2004 Statewide High Consumption Event Day Load Curves



Non-event day performance of high consumption ADRS homes exhibits similar patterns as event days. For high consumption ADRS customers, peak period load reduction was 0.86 kW or 32% relative to control homes in 2004, compared to 0.73 kW or 27% reduction in 2005, statewide. Unlike event days, however, the smaller peak period load reduction on non-event days in 2005 compared to 2004 is attributed mostly to higher average summer season temperatures in 2005. Both high consumption ADRS and control customers had higher peak period demand in 2005. However, control load increased by 4% during the peak period in 2005, while ADRS load increased by 12% during the peak period. Note also that ADRS loads dropped further at 2 p.m. in 2005 than 2004, but recovered more quickly throughout the rest of the peak period, which is consistent with the observation that hotter summer weather causes the indoor temperatures to rise to the on-peak thermostat set-point faster. This results in modestly diminished ADRS savings, statewide.

Table 1. Comparison of Super Peak Period Load Reductions for High Consumption ADRS Homes, Summer (July – September) 2005 and Summer 2004

	Event Days 2005			**Event Days 2004**		
	Average reduction, kW	5-hour total, kWh	% Reduction	Average reduction, kW	5-hour total, kWh	% Reduction
PG&E	0.8	4.2	29%	1.3	6.4	39%
SCE	1.9	9.2	49%	2.4	11.9	58%
SDG&E	1.2	5.8	38%	1.2	6.0	41%
Statewide weighted average	1.4	7.1	43%	1.8	9.2	51%

Table 2. Comparison of Peak Period Load Reductions for High Consumption ADRS Homes, Summer (July – September) 2005 and Summer 2004

	Non-Event Days 2005			**Non-Event Days 2004**		
	Average reduction, kW	5-hour total, kWh	% Reduction	Average reduction, kW	5-hour total, kWh	% Reduction
PG&E	0.5	2.4	18%	0.6	2.7	22%
SCE	0.9	4.5	30%	1.1	5.6	38%
SDG&E	0.7	3.5	27%	0.4	1.9	17%
Statewide weighted average	0.7	3.7	27%	0.9	4.3	32%

Results differed by utility (Table 1 and Table 2). Load reduction of high consumption ADRS homes within each utility service territory were substantial during both years, although performance was slightly better in 2004 than in 2005, with the exception of SDG&E, due to the unusual behavior of the control group as mentioned above. SCE high consumption ADRS customers achieved on average about 2 kW reductions on event days across a range of temperatures. PG&E and SDG&E high consumption ADRS customers achieved substantial, but lower reductions, close to 1 kW on event days on average[3]. Load reduction impact of ADRS homes in SDG&E territory should be interpreted with caution, however, due to the small sample size. In SDG&E territory, just 7 high consumption homes participated in the program in 2004 and only 6 homes in 2005.

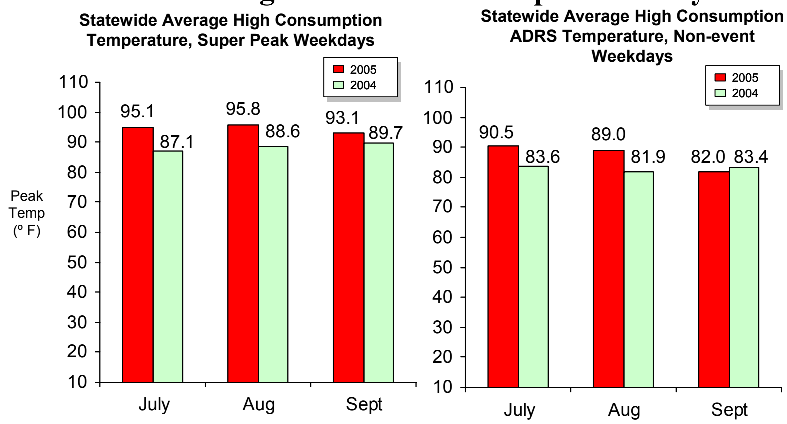
Figure 2 confirms that the program during 2005 recorded higher temperatures than during 2004, on event and non-event days. On both event and non-event weekdays statewide, temperatures were nearly 8°F warmer in 2005 during both July and August. September temperatures were closer between the two summers, with 2005 event day temperatures

[3]It is not applicable to compare results across utilities, because each utility ran the ADRS pilot within their service territories independently of each other. As such, there are numerous controllable and uncontrollable factors that would need to be held constant in order for a valid utility comparison to take place. However, one cannot help but observe and speculate why SCE pilot performance was consistently stronger than ADRS customers in PG&E and SDG&E territories. Some factors that appear to provide a strong link to better program performance in SCE territory is that ADRS homes were recruited from residential developments that homes tended to be larger than ADRS homes from zip codes targeted in PG&E and SDG&E territory, on average. About 40% of SCE customers owned homes with floor areas larger than 2,000 sq.ft., compared to about 30% and 20% for ADRS customers in PG&E and SDG&E service territories, respectively. Furthermore, the majority of ADRS participants (59%) in SCE territory had household incomes greater than $100,000 per year. These homes also tended to have larger air conditioning units, on average 4 tons cooling capacity per unit, and more likely to have additional controllable loads such as swimming pools.

exceeding 2004's by 3°F. Non-event day temperatures in September were essentially the same in 2004 and 2005, on average statewide.

Utility-specific temperatures exhibited similar patterns with the exception of PG&E, where average event day temperatures were higher in September 2004 than in September 2005. Both PG&E and SCE experienced average temperatures in the range of 89°F to 98°F on event days and between 80°F to 95°F on non-event days. Temperatures in SDG&E territory, on the other hand, experienced temperatures that were on average 10°F cooler, between 76°F and 88°F on both event and non-event days.

Figure 2. 2005 and 2004 Average Peak Period Temperatures by Month, Statewide



Percentage load reductions during each hour of the Super Peak period between 2004 and 2005 of high consumption ADRS customers compared to control customers are plotted in Figure 3, using results from PG&E service territory as an example. Like absolute load impact, percentage reductions were consistently less in 2005 than in 2004. As noted before, this was mostly due to a lower relative 2005 control load during the peak period, resulting in lower savings in 2005. Nevertheless, Super Peak performance in high consumption ADRS homes was reliable over consecutive years.

Both years show the same downward trend in load reduction over the duration of the Super Peak period. In 2005, ADRS load reductions in PG&E territory fell more substantially between the first and last hours of the Super Peak period than in 2004. For SCE service territory, however, high consumption ADRS load reductions in both years were relatively constant during the first three hours of the Super Peak period before attenuating during hour 4 and 5. Hourly percent reductions for ADRS homes in SDG&E territory steadily declined from hour 1 to 5 as with PG&E, though relative performance between 2005 and 2004 were quite similar compared to 2004 for the first four hours, with differences of only 5% on average.

Figure 3. 2004 and 2005 Super Peak Hourly Percent Load Reductions, High Consumption ADRS Homes, PG&E Territory

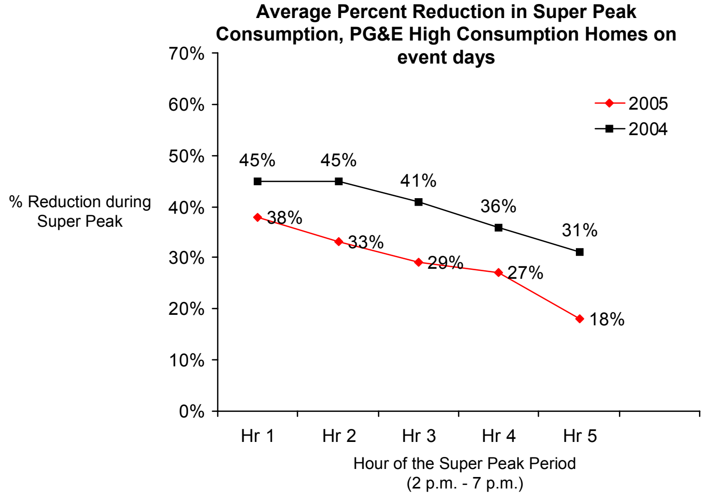
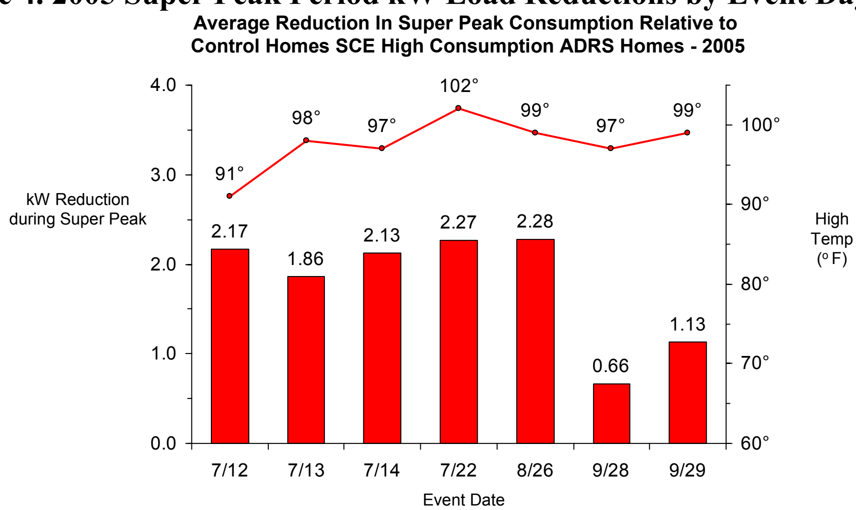


Figure 4 and Figure 5 displays the ADRS load reductions for each event day in 2005 and 2004, respectively, using results in SCE service territory as an example. Average Super Peak temperatures on the corresponding event days are plotted on a secondary axis in both charts. Performance was generally strong and sustained across the summer and across a range of temperatures. Load reductions in 2004 were slightly higher than in 2005.

Figure 4. 2005 Super Peak Period kW Load Reductions by Event Day, SCE



Super Peak period load reductions in 2005 were greatest in July and August, while in 2004 performance was greatest in September. This pattern is also true for PG&E. This may be due in part to the timing of the event days in 2005 at the end of September with associated changes in ADRS consumption behavior in anticipation of autumn. In contrast, September event days in 2004 were called early in the month, just after Labor Day weekend. In SDG&E service territory, however, high consumption ADRS load reduction was strongest in September for both years. This is likely because average temperatures experienced by ADRS homes were relatively warm in September (86.5°F in 2005 and 81.0°F in 2004) on event days, compared to July (78.7°F in 2005 76.9°F in 2004).

Figure 5. 2004 Super Peak Period kW Load Reductions by Event Day, SCE

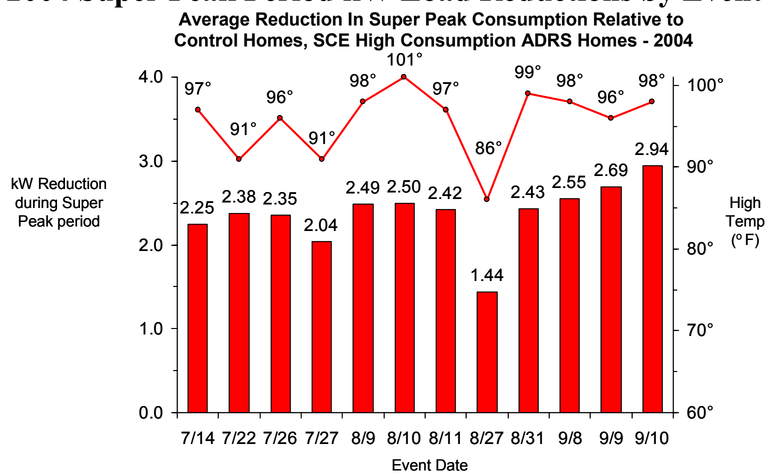


Figure 6 juxtaposes percent load reductions over consecutive event days for 2004 (right) and 2005 (left), using SDG&E service territory as an example. Consecutive event days in 2004 showed slightly higher percent reductions than in 2005, though with similar variability between ADRS load reductions compared to control. Looking across both years, there does not appear to be any particular trend in consecutive day percent reductions, although a good but not particularly strong relationship with average peak temperature on corresponding event days. Consecutive event day reductions in PG&E and SCE territories exhibit similar performance and consistent patterns compared to SDG&E for 2005, but with higher variability in behavior for 2004.

Figure 6. Consecutive Event Day Super Peak Period Percent Reductions in 2005 and 2004, SDG&E High Consumption ADRS Homes

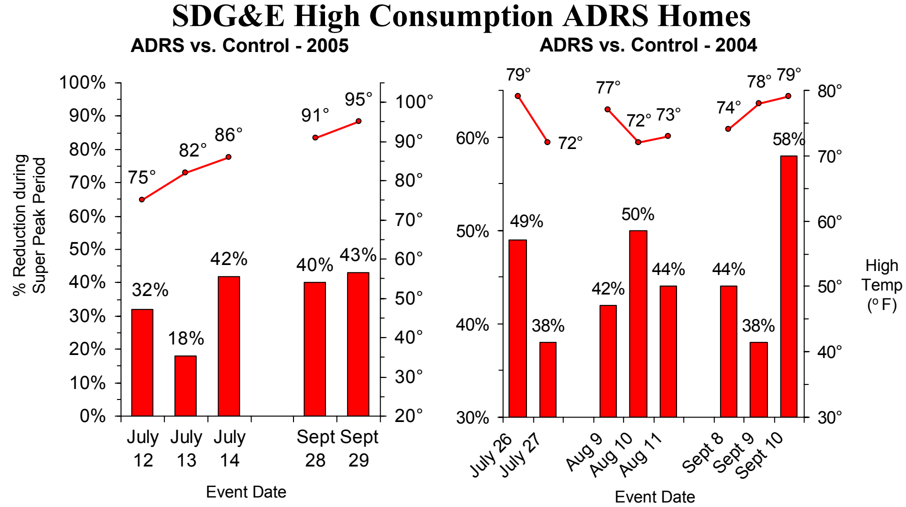


Figure 7 and Figure 8 segment average daily consumption in kWh of ADRS and control customer loads into peak (2 p.m. – 7 p.m.), recovery (7 p.m. – 9 p.m.), and off-peak periods for 2005 and 2004. The statewide weighted average results are shown. In both figures, event day averages are shown on the left and non-event weekdays are shown on the right. Because of load reductions during Super Peak periods, ADRS high consumption homes consumed less energy than control homes during the period in both 2004 and 2005. The shifting of load away from the Super Peak period in ADRS homes is apparent in the relatively higher ADRS consumption in recovery and off-peak periods in 2005 and 2004. During the recovery period from 7 p.m. to 9 p.m. on event days, ADRS customer consumption rebounded to exceed control consumption as ADRS thermostats were reset to off-peak period set points. ADRS homes also consumed more than control homes in the off-peak periods on event days in 2005. Off-peak period consumption on event days between ADRS and control customers was the same in 2004, statewide.

Figure 7. 2005 kWh Usage by Period, High Consumption Homes Statewide

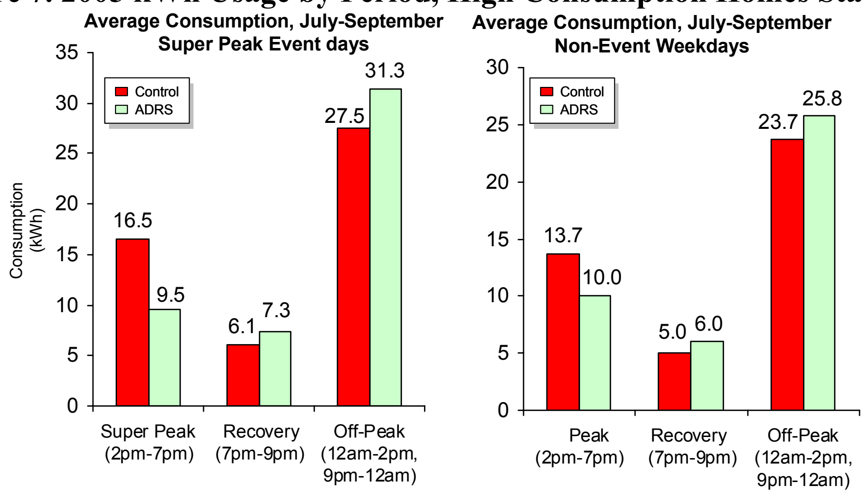
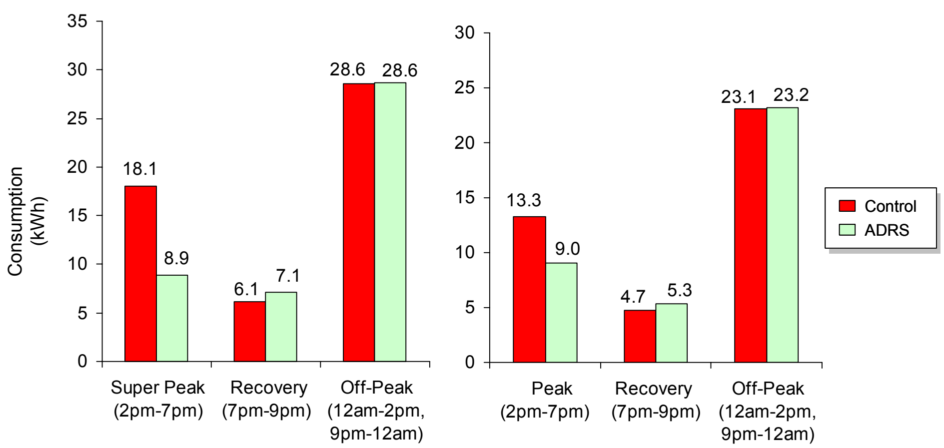


Figure 8. 2004 kWh Usage by Period, High Consumption Homes Statewide

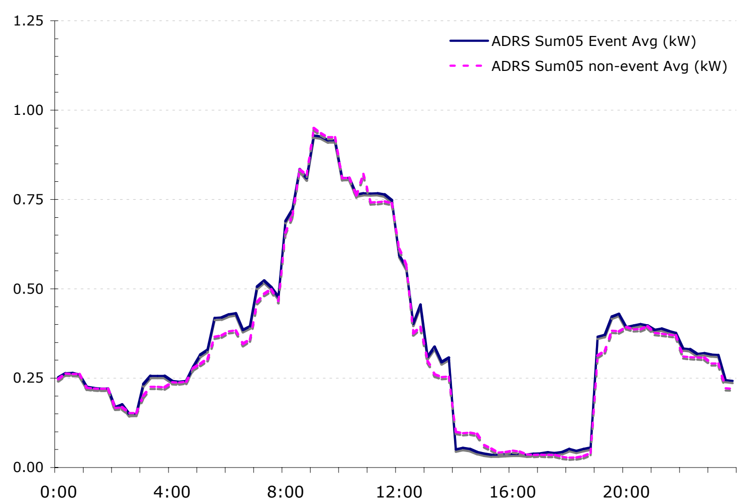


Non-event day consumption patterns in 2005 and 2004 show the same trends as event days. Differences between ADRS and control customers were more modest in 2004 statewide for recovery and off-peak periods. The 2005 non-event day peak period reductions represent load shifting to off-peak periods rather than overall reduction in energy consumption over the whole day. On the other hand, both load shifting and energy conservation were present during 2004 non-event weekdays.

Comparing daily energy consumption patterns between years by utility, high consumption ADRS customers in PG&E and SCE service territory shifted load more aggressively from Super Peak and peak periods to off-peak periods in 2005 compared to 2004, with subsequent reductions in net energy conservation. High consumption ADRS homes in SDG&E service territory, on the other hand, appeared to have used technology to reduce overall energy consumption as opposed to merely shifting load on both event and non-event days, for both summer 2005 and summer 2004. It may be that in SDG&E, where average temperatures were typically 10^{o}F cooler that the statewide average, customers were better able to respond to peak pricing signals by reducing energy consumption overall. In PG&E and SCE service territory where temperatures tended to be higher than the statewide average, high consumption ADRS customers resorted to shifting load in order to save money using automated technology.

In addition to load reduction from central air, the ADRS program also curtailed pool pump load, for homes with swimming pools. A typical pool pump operates continuously for four to eight hours each day. Owners typically schedule operation during daylight hours when the chlorine cycle is most efficient. Figure 9 shows the average aggregated load of pools in the program in 2005 (total 33 pools) operating on weekdays versus curtailed days. Note that load curves reflect load diversity, as an individual pump peaks at approximately 1.6 kW.

Figure 9. Average High Consumption ADRS Pool Pump Load, July-September 2005



The average daily load curve shows that high consumption ADRS customers with swimming pools consistently scheduled pool pump operation outside of the hours between 2 p.m. and 7 p.m. to reduce Super Peak and peak period consumption every day. Residents shifting pool pump operation contribute 32% of total Super Peak reduction for an average home with a pool. Since approximately one out of every three ADRS participant owns a pool, this load reduction contributed about 10% of total Super Peak period reduction on event days. On non-event days, residents shifting pool pump operation contributed over 50% of total peak period reduction for an average home with a pool. This load reduction contributed about 27% of total peak period reduction on non-event days.

Conclusions

Customers with ADRS technology and subject to CPP-F rates in climate zone 3 successfully achieve load reductions compared to control customers without ADRS technology on standard tiered rates in both 2005 and 2004. The load reductions were substantial and stable across a range of days and temperatures. Technology appears to be an important driver in reducing load, especially Super Peak load, for high consumption customers.

Load reduction performance for ADRS customers varied between utilities across the state. SCE high consumption ADRS customers achieved on average about 2 kW reductions on event days across a range of temperatures. PG&E and SDG&E high consumption ADRS customers achieved substantial, but lower reductions, close to 1 kW on event days on average.

Comparing daily consumption patterns between years in energy terms, high consumption ADRS customers in PG&E and SCE service territory were more aggressively shifting load from Super Peak and peak periods to off-peak periods in 2005 compared to 2004, with subsequent reductions in net energy conservation. High consumption ADRS homes in SDG&E service territory, on the other hand, appeared to have used technology to reduce overall energy consumption as opposed to shifting load on both event and non-event days, for both summer 2005 and summer 2004.

Where present, pool pumps made a significant contribution to reduction of Super Peak and peak period load. Examination of average daily load profiles showed that high consumption ADRS customers with swimming pools consistently scheduled pool pump operation outside of the hours between 2 p.m. and 7 p.m. to reduce Super Peak and peak period consumption every day. On event days, pool pumps operation contributed 32% of total Super Peak reduction for an average high consumption ADRS home with a pool. On non-event days, residents shifting pool pump operation contributed over 50% of total peak period reduction for an average home with a pool.

Acknowledgements

The authors gratefully acknowledge the contributions of L. Morton and E. Wanless for their work on the original version of this document.