The Day the Engineers Were Right: Confirming the Peak Demand Reductions of FPC's Air Conditioner Duct Test and Repair Program

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This paper assesses the reduction in summer system peak demand that resulted from implementation of Florida Power Corporation's (FPC's) Air Conditioner Duct Test and Repair (A/C Duct) Program.

To estimate the reduction in summer peak demand attributable to this program, two separate research designs are presented. The first relies on metered HVAC circuits for program participants only. Metered data from pre- and post-repair periods are weather-adjusted and compared to determine summer peak demand reductions. The second research design relies on whole-house metered data for program participants and nonparticipants from pre- and post-repair periods. These data are then augmented with customer survey responses from which a participation decision model and a demand impact model are developed.

Of the two analyses, the air conditioner demand analysis is considered as more reliable evidence of the program summer peak demand reduction. The primary reservation regarding the use of participant and nonparticipant whole building data to estimate net program impacts is that whole building metering incorporates all the home equipment and appliances, not just the air conditioner. As such, it provides less precise measurement of the hourly load of the equipment of interest. In contrast, by directly metering the participant air conditioner circuits prior to, and following, duct repairs, a more precise measurement is available. For this reason, the air conditioner metered data analysis of the participants only is viewed as the more reliable research design of the two presented.

The estimated average summer peak demand savings is 0.49 kW with a relative precision of 32 percent at the 90 percent confidence level. This closely agrees with the engineering estimated program impact of 0.50 kW.

Introduction

This paper assesses the reduction in summer system peak demand that resulted from implementation of Florida Power Corporation's (FPC's) Air Conditioner Duct Test and Repair (A/C Duct) Program. The evaluation draws on load research data collected for a sample of program participants and nonparticipants in the summer of 1992.

FPC's procedure for implementing this program, as well as most of its other residential DSM programs, was to use the Home Energy Audit Program to screen for eligible participants. Once his/her needs were determined, the customer was encouraged to participate in one or more additional FPC programs, as appropriate. As such, participation in the Home Energy Audit Program was a prerequisite for participation in the A/C Duct Program.

Through the A/C Duct Program, FPC encouraged eligible customers to inspect and repair their home duct systems. To participate, the Home Energy Audit Program indicated that the building was likely to benefit from duct inspection and repair, and that the building's duct system was in good enough condition for the duct test to be performed. As an incentive to participate, FPC paid half of the home inspection cost up to $25, and half of the repair cost up to $100.

To test for air leakage, the duct inspection method consisted of mechanical pressurization of the building and its central duct system. From the relationship between the air flow rates and pressure differentials, first with the duct system operating normally, and then with the duct system sealed from interior air, the central duct system air leakage was estimated. The scope of the repairs to the duct and/or to the interstitial building components used as a duct was based on these findings. The program was first offered in April 1991. Through December 31, 1992, over 9,000 customers had participated in FPC's A/C Duct Program.

To estimate the reduction in summer peak demand attributable to this program, two separate research designs are presented. The first relies on metered HVAC circuits for program participants only. Metered data from pre- and post-repair periods are weather-adjusted and compared to determine summer peak demand reductions. The second research design relies on whole-house metered data for program participants and nonparticipants from pre- and post-repair periods. These data are then augmented with customer survey responses from which a participation decision model and a demand impact model are developed.

The second section of this report describes the data collection efforts, including site recruitment and meter installation. The third section analyzes hourly air conditioner demand data and hourly whole building demand data. The fourth and final section of this report offers conclusions and recommendations.

Data Collection

Site Selection and Recruitment

Participants that were recruited as metered sites for this evaluation included those customers receiving an FPC home energy audit who were solicited by FPC field representatives in June and July of 1992 to participate in the A/C Duct Program. Clearwater and Orlando were the two regions from which sites were chosen, primarily because they contained the largest proportion of participants in the program. The Tallahassee region, which had very few program participants in the summer of 1992, was excluded from the study.

If the customer indicated an interest to participate in the A/C Duct Program, the FPC representative inquired about his/her interest in participating in a load research study. Customers with a positive response were further screened prior to site recruitment. These customers were asked:

- if they intended to leave their home for more than four consecutive days during the study period of July, August and September;
- if the number of home occupants or house guests over the study period was likely to increase;
- if they intended to undertake major repairs, renovations or remodeling over the study period;
- if they were willing to postpone participation in the duct repair program for two months; and,
- if they resided in single family homes that were larger than 1,000 square feet, did not have jalousie windows, and had air conditioning systems that were less than 20 years old.

Those customers that met these initial screening criteria were recruited as a study site immediately following the A/C duct test. At this time, the FPC contractor was instructed to rank, on a scale from one (low) to five (high), the potential level of energy savings from duct repair. If the FPC contractor estimated moderate, or higher than moderate, energy savings (a score of four or more), the contractor was authorized to offer the customer an incentive of $100: $75 payable upon installation of the metering equipment and $25 payable upon removal of the equipment. However, the customer had to agree to allow the data-logging equipment to be installed and removed, and to accept postponement of the duct repairs until two to four weeks after the data-logging instruments were put in place.

Site selection and recruitment began in June and were discontinued in early August. Recruitment activity ceased when a home's post-repair study period could no longer be expected to span more than one or two weeks of the peak cooling season. Typically, in central Florida this season ends in late September. Since the time required for duct test scheduling, the pre-repair period, and the repairs themselves normally took at least six weeks, a recruited site would no longer be useful for the study after the second week in August.

The nonparticipant sample was matched to the participant sample to assure representativeness. For each participant, two nonparticipants were selected for whole building load metering. The nonparticipants selected were located on the same meter reading route as the participants. In addition, August 1991 energy use was used to match the participant and nonparticipant customers.

The strength of this technique is that it does not rely on chance to select a small sample of customers from among FPC's large customer base to be representative of program participants. Further, it does not require customer-specific data to draw a sample that controls for locational and socio-economic effects. To the degree that neighborhoods are relatively homogeneous with respect to income, culture, demographics and housing stock, the energy use of the matched nonparticipants can be assumed to represent what the energy use of the participants would have been in the absence of duct repairs.

There is a drawback to a pairwise sampling technique. Using random sampling, all observations are drawn independently and thus the loss of an observation has no repercussion other than to diminish the sample size. Alternatively, pairwise sampling closely links each set of participants and nonparticipants, and thus the loss of an observation must result in the loss of its corresponding observation; failure to do so would lead to sample bias. For this reason, customers were excluded from the analysis if there was no accompanying matched customer. In other words, a metered, surveyed participant without at least one matching, metered and surveyed nonparticipant was dropped from the study. Likewise, a surveyed, metered nonparticipant without a matching metered, surveyed participant was dropped from the study.

Meter Installation

Process Systems ProData S-100ST Recorders were installed in the program participant and nonparticipant homes by FPC Meter Department personnel. The whole house load was metered using a standard meter with pulse initiator, and ProData ADD1 receivers and ProData ADD1 Transponders monitored HVAC loads. In all, meters were installed in the homes of 115 program participants and 230 program nonparticipants.

The metering equipment used for this study were originally purchased in 1986. The transponder/receiver system for the end-use metering, based on an uncoded power line signal, had been used in several previous end-use studies. Considering the age of the equipment and past problems, FPC elected to double meter the HVAC loads wherever the electrical system made it possible. Approximately half the test group had their HVAC loads metered with two independent transponders. HVAC loads were not metered for program nonparticipants.

The metering devices were put in place for up to four weeks prior to, and up to four weeks following, the duct repairs. If a home was also participating in FPC's direct load management program, the load management equipment was disabled for the study period. Data verification consisted of two steps. The first step, where there was double metering, was to compare the HVAC load profiles to each other. The second step was to compare the profiles of the whole house load with that of the HVAC load. In all, data from about 67 percent of the residences were considered valid. If redundant metering had not been used, the percentage of valid data would have decreased to about 60 percent.

Time Frame and Sample Size

To measure the change in loads over the summer cooling season, the pre-repair period for the metering took place over July and August 1992, and the post-repair period over August and September of 1992. The actual number of days, and the exact dates for the pre- and post-repair periods, varies for each participant, depending on the following factors:

1. Customer duct test recruitment. Customers were contacted by field representatives throughout June, July and early August;

2. Duct test and repair scheduling. After customers agreed to participate, the test and the repairs had to be scheduled with FPC's licensed contractors; and,

3. Data screening. For some customers, the data for certain days were excised due to poor quality, repairs that had to be redone, or periods of extended occupant vacancy.

For nonparticipants the pre- and post-repair period was defined based upon the matching participant repair data. The final sample size for the air conditioner demand analysis consisted of 61 participant homes. For the whole house demand analysis, participant homes and 25 nonparticipant homes were available.

Hourly Impact Analysis

Air Conditioner Metered Data

Weather-adjustment of Demand. Before hourly air conditioner demand in the pre- and post-repair periods can be compared, it is necessary to statistically adjust the levels of demand in each period for differences in temperature. Doing so ensures that the estimated difference in demand between periods is not biased by the one period having experienced different temperatures than the other.

To initiate the statistical analysis, the fifteen-minute interval load data collected by the data loggers were combined to create average hourly kW demand. After constructing hourly demand, the data were screened for zero reads and outliers. Weekday load data were separated from weekend and holiday data so that the statistical analysis could be performed individually for the two different day types.

To perform the weather-adjustment efficiently, a single regression model specification was developed, using hourly temperature data and daily periods as the independent variables. This specification was designed to mirror the major characteristics of the average, raw (or nonweather-adjusted), program-weighted, mean load shapes. Examples are displayed in Figures 1 and 2.

As the figures reveal, the load shapes have a non-linear form that can roughly be broken into four periods. These are the off-peak period from midnight through 08:00 (OFF_PEAK), the morning shoulder period from 09:00 through noon (SHOULDER1), the peak period from 13:00 through 19:00 (PEAK), and the evening shoulder period from 20:00 through 23:00 (SHOULDER). Also notable about the load shapes, the air conditioner load peaks at 17:00.

Average hourly temperature profiles are also displayed in the figures. These profiles are similar to the load shapes and can be viewed as having four well-defined periods. The profile reveals that temperature peaks about four hours earlier than the air conditioner load, at 13:00. The temperature profiles and the load shapes appear to be similar across both day types.

To preserve the basic characteristics of this load shape, the hourly weather-adjustment model takes the form:

$$AC\_KW_h = \alpha_0 + \alpha_1(TEMP_h) + \alpha_2(LAG + TEMP_H)$$
$$+\alpha_3(SHOULDER1) + \alpha_4(PEAK)$$
$$+\alpha_5(SHOULDER2) + \alpha_6(TEMP_h{}^*SHOULDER1)$$
$$+\alpha_7(TEMP_h{}^*PEAK) + \alpha_8(TEMP_h{}^*SHOULDER2)$$
$$+\varepsilon_h$$

where α_0 through α_8 are model coefficients; AC_KW_h and $TEMP_h$ are hourly values for hour h; $TEMP_h$ is the dry bulb temperature taken at Clearwater and Orlando airports, respectively; LAG_TEMP_h is the hourly temperature lagged four hours; and the daily periods SHOULDER1, PEAK and SHOULDER2 are defined as above and coded as 0,1 indicator variables. The model error term is assumed to be independent.

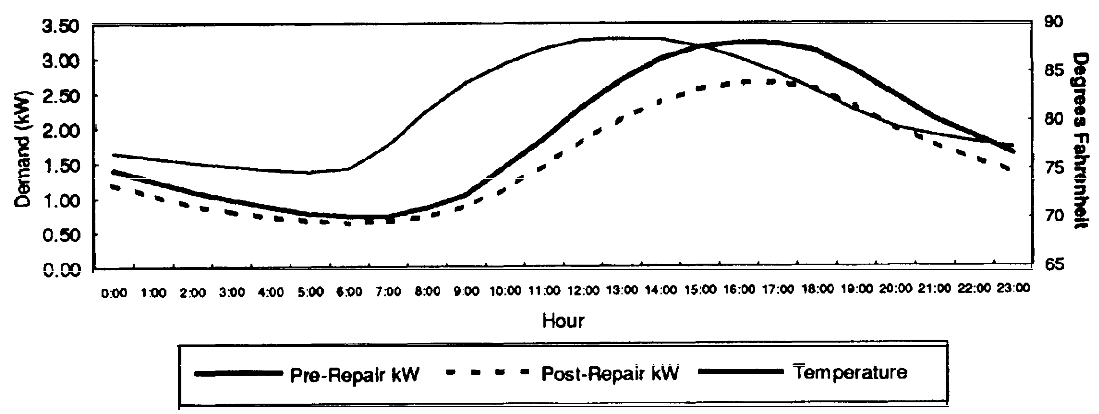

Figure 1. Average Weekday Pre- and Post-Repair Period A/C Load Shape and Average Hourly Temperature

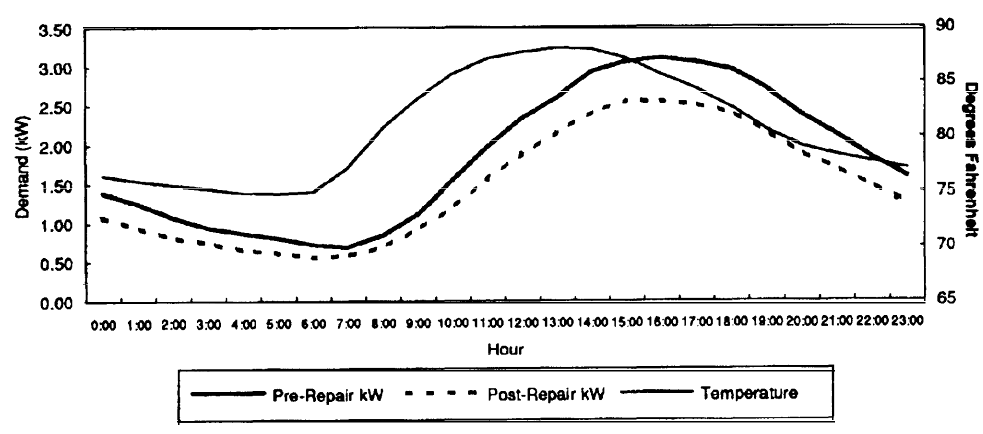

Figure 2. Average Weekend Pre- and Post-Repair Period A/C Load Shape and Average Hourly Temperature

The three daily period indicator variables, along with the three interaction terms ($TEMP_h$*SHOULDERl, $TEMP_h$*PEAK and $TEMP_h$*SHOULDER2), allow this model the flexibility to capture the non-linearities in the daily load shape. The indicator variables themselves allow the "level" of demand to shift with each period, while the interaction terms allow the "rate of marginal change" of demand to shift over each period.

For each of the 61 homes that remained in the study sample following the data screening, four regression models were estimated: one for each of the two day types (weekday and weekend/holiday) in the pre-repair period, and one for each of the two day types in the post-repair period. Figure 3 and Figure 4 exhibit the average, program-weighted, weather-adjusted load shapes for the two day types in the pre and post-repair periods.

System Peak Hour Program Impacts. Weather-adjusted hourly values are calculated by forecasting each customer's hourly demand using the estimated model parameters given the system peak day temperatures. For this study, the system peak day temperatures were derived by taking the average hourly temperature for the system peak day of each of the last thirty years. For each customer's four models, the weather-adjusted, long-run hourly air conditioner load was forecasted using the following equation:

$$\begin{aligned} LRAC\_KW_h = {} & \alpha_0 + \alpha_1(LRST_h) \\ & + \alpha_2(LAG\_LRST_h) + \alpha_3(SHOULDER1) \\ & + \alpha_4(PEAK) + \alpha_5(SHOULDER2) \\ & + \alpha_6(LRST_h{}^*SHOULDER1) \\ & + \alpha_7(LRST_h{}^*PEAK) \\ & + \alpha_8(LRST_h{}^*SHOULDER2) \end{aligned}$$

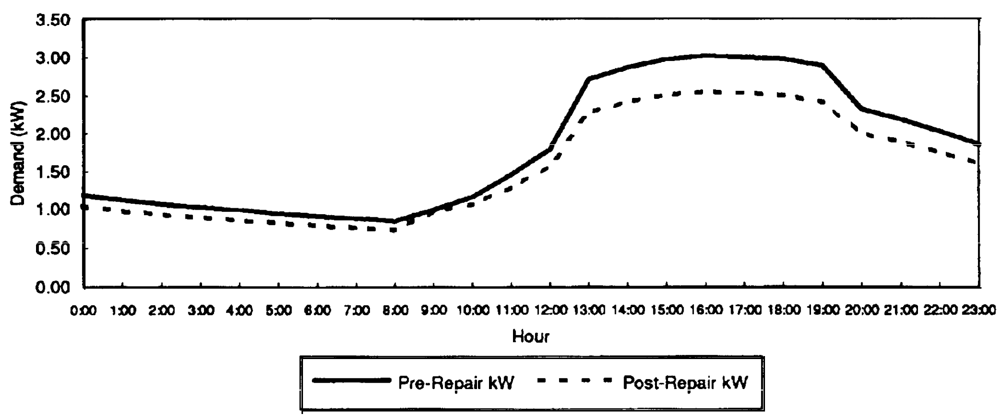

Figure 3. Weather-Adjusted Average Weekday Pre- and Post-Repair Period A/C Load Shape

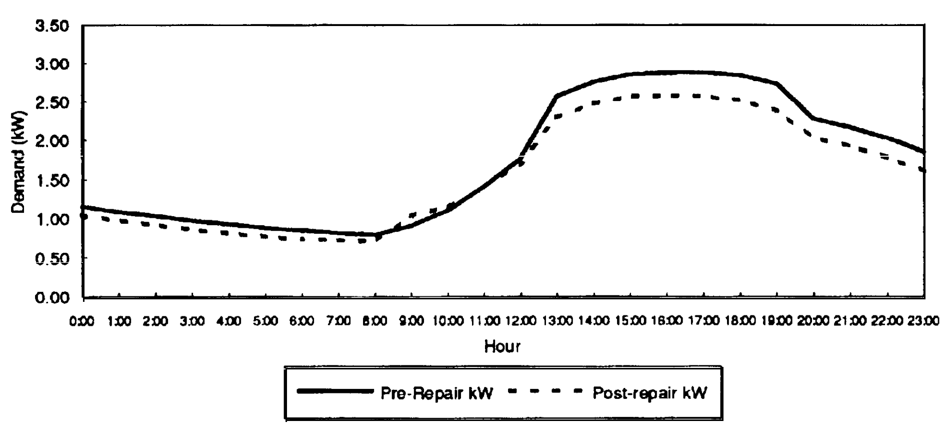

Figure 4. Weather-Adjusted Average Weekend Pre- and Post-Repalr Period A/C Load Shape

where $LRAC\_KW_h$ is the weather-adjusted, long-run, hourly air conditioner demand and $LRST_h$ is the average system peak day summer temperature for hour h (for either the Clearwater or Orlando region). The average load shape is constructed by averaging the weather-adjusted demand for each customer, by each hour.

To derive program impacts, the average, weather-adjusted, peak day demand for each hour in the pre-repair period is subtracted from the same hourly value for the post-repair period. The values for the Clearwater and Orlando regions are then combined and weighted by the proportion of program participation in each region from the beginning of the program through the end of 1992. Based on program data the Clearwater region was given a weight of 53.5 percent and the Orlando region was given a weight of 46.5 percent. The findings for the peak day weekday hours are displayed in Table 1 along with the accompanying standard errors and relative precision for each hour, at the 90 percent confidence level. The relative precision is calculated by multiplying the weighted standard error of each hour by a t value of 1.645 and dividing this product by the weighted hourly mean.

The peak day findings reveal that demand is reduced by 0.49 kW at 17:00, a reduction of approximately 14 percent of air conditioner load. The relative precision of the estimate at the 90 percent confidence level is approximately 32 percent. Translated into error bounds, this means that there is a 90 percent chance that the peak day program impact for 17:00 is a reduction of between 0.33 kW and 0.65 kW of air conditioner load.

Whole Building Metered Data

In the whole building metered data research design, two interrelated regression models are estimated, one to estimate the probability of program participation and the other to control the differential effects of household characteristics and self-selection on hourly demand. To collect data for estimating these models, a telephone survey was administered to metered participants and nonparticipants. For each of these models, the sample consisted of only those pairs of participants and nonparticipants who were metered and who responded to the telephone survey. In all, 19 participants and 25 nonparticipants were included in the models. The two models are:

- A participant decision model that estimated the probability of a customer participating in the A/C Duct Program. This model provides quantitative estimates of the probability of participation by examining key variables that may be related to a propensity for program participation. With the model, a variable is created that is incorporated into a multiple linear regression model of customer energy consumption. Inclusion of this variable in the multiple linear regression model ensures that the estimate of mean program-related energy savings is not biased by changes in energy use that are a result of one group of customers being different from the other group of customers with respect to how much they benefit from program participation.

Table 1. Independent Variables in the Participant Decision Model

NET_REP	=	Whether customer has installed energy conservation measures without FPC's assistance (0,1)*
ROOMS	=	Number of rooms in house
FULLTIME	=	Number of people with full-time employment outside of house
EDUC1	=	Head of household highest education level graduate school (0,1)*
EDUC2	=	Head of household highest education level completed college (0,1)*
WINFIVE	=	Plan to sell house within five years (0,1)*
HIGHSAVE	=	Anticipate greater than 15 percent saving on electricity bill for duct repair work (0,1)*

* A coding of (0/1) indicates that it is an indicator variable with a value of 1 representing an affirmative response.

- An hourly whole building demand model in which the change in participant and nonparticipant demand for the system peak hour from pre- to post-repair periods is explained as a function of key variables, such as household demographics, major household appliances, location, and the propensity to participate as calculated in the participant decision model.

Participant Decision Analysis. The variables selected for the A/C Duct Program participation decision model come from the customer telephone survey. Variables were excluded from the model if they contained a large percentage of missing values, since a missing value for a single variable will result in the entire observation being dropped from a regression model. Table 1 contains brief descriptions of the independent variables contained in the A/C Duct Program participation decision model.

The estimated model stabilized after four iterations. Based on the "-2 log likelihood ratio test" statistic, the model is not statistically significant (probability level equal or greater than 0.95). Practically speaking, this means that the model does not detect a strong, systematic distinction between participants and nonparticipants, i.e., it does not appear self-selection is present with respect to the variables tested in the model. The model estimates are displayed in Table 2.

The participant decision model is used to calculate the probability of each customer participating in the A/C Duct Program. Next, the inverse mills ratio is calculated. This variable controls for the variance in the change in energy use that may occur if there are systematic differences in participants and nonparticipants that are related to their propensity to participate in the A/C Duct Program. It is often referred to as a "self-selection correction term."

Peak-day Demand Impact Analysis. The aim of developing a multiple linear regression model of whole building demand on the peak day at 17:00 is to simultaneously control for key variables that differentially affect demand for participants and nonparticipants. This is done by specifying and estimating a multiple linear regression model in which the variance in the change in customers' peak day demand is explained by key household characteristics and whether or not the customer participated in the A/C Duct Program.

To derive an estimate of program impacts, a model was specified in which peak hour demand in the post-repair period was regressed on independent variables that are related to peak hour demand. The general model is:

$$POST\_KW_i = \beta_1 + \beta_2(PRE\_KW_i) + \beta_3(CHARACT_i) + \beta_4(MILLS_i) + \beta_5(PART_i) + \varepsilon_i$$

where:

$POST\_KW_i$ = post-repair, weather-adjusted hourly demand at 17:00 for customer i;

Table 2. Participation Decision Model Dependent Variable: Participation

Independent Variables	Parameter Estimate	Standard Error	Probability
Intercept	-1.05	1.89	0.58
NET_REP	-0.49	0.69	0.48
ROOMS	0.24	0.29	0.42
FULLTIME	-0.09	0.38	0.81
EDUC1	-0.78	0.84	0.35
EDUC2	-0.32	1.07	0.76
WINFIVE	-0.23	0.87	0.8
HIGHSAVE	-0.09	1.05	0.93
n	44		
Log Likelihood at Convergence	58.07		
Chi-square at Convergence	2.11		(p=0.95)

PRE_KW_i = pre-repair, weather-adjusted hourly demand at 17:00 for customer i;
$CHARACT_i$ = a vector of variables related to customer characteristics affecting hourly demand for customer i,
$MILLS_i$ = participation correction term for customer i;
$PART_i$ = dummy variable representing program participation for customer i;
ϵ_i = model error term.

A brief description of each independent variable is contained in Table 3.

Table 4 displays the estimated findings for this model. The most important finding of this model is that the mean estimated net reduction in peak day demand at 17:00 is 0.74 kW. The relative precision of this estimate at the 90 percent confidence level is 59 percent, implying that there is a 90 percent chance that if reduction in peak demand were known for the entire population of participants, it would be between 0.30 kW and 1.18 kW per participant.

Many of the variables included in the demand analysis model are not statistically significant at the 90 percent confidence level. However, exclusion of these variables from the model does not affect the program savings estimate.

Conclusion

In conclusion, the two research designs presented offer highly reliable evidence that the program is achieving its demand reduction goal. Average summer peak demand savings is estimated as 0.49 kW for air conditioner metered analysis and 0.74 kW for the whole house metered analysis, while the goal of the program is a reduction of 0.50 kW.

Of the two analyses, the air conditioner demand analysis is considered as more reliable evidence of the program summer peak demand reduction. The primary reservation regarding the use of participant and nonparticipant whole building data to estimate net program impacts is that whole building metering incorporates all the home equipment and appliances, not just the air conditioner. As such, it provides less precise measurement of the hourly load of the equipment of interest. In contrast, by directly metering the participant air conditioner circuits prior to, and following, duct repairs, a more precise measurement is available. For this reason, the air conditioner metered data analysis of the participants only is viewed as the more reliable research design of the two presented.

Table 3. Description of the Independent Variables in the Multiple Regression Demand Analysis Model

PRE_KW	=	Pre-repair, weather-adjusted system peak demand
P1	=	Number of people over 65 years
P2	=	Number of people 31 to 65 years
P3	=	Number of people 15 to 30 years old
CHANGE	=	Number of hours AC consumption has changed since program participation
DAYTIME	=	Number of people home 4 or more hours during daytime
POOL	=	Whether household has a pool (0/1)*
DHW	=	Whether household has an electric water heater (0/1)*
MILLS	=	Participation correction term
PART	=	AC Duct Repair Program participant (0/1)*
CLEARWATER	=	Location in Clearwater Region (0/1)*

* A coding of (0/1) indicates that it is an indicator variable with a value of 1 representing an affirmative response.

Table 4. Multiple Regression Demand Analysis Model Dependent Variable = POST_KW

Independent Variables	Parameter Estimate	Standard Error	Probability
Intercept	1.48	0.89	0.11
PRE_KW	0.81	0.09	0.00
P1	-0.22	0.19	0.26
P2	-0.33	0.18	0.08
P3	0.29	0.17	0.09
CHANGE	-0.07	0.08	0.36
DAYTIME	0.09	0.10	0.35
POOL	0.01	0.30	0.97
DHW	-0.54	0.83	0.52
MILLS	0.0023	0.012	0.84
PART	-0.74	0.27	0.01
CLEARWATER	0.21	0.27	0.43
n	44		
Dependent Variable Mean	4.37		
Root Mean Square Error	0.73		
Adjusted R-square	0.79		