Adapting to the Adaptations: Smart Methods for Smart Control

Miriam Goldberg, Ken Agnew, Paula Ham-Su, KEMA Inc.

Mike Alexander, Pacific Gas and Electric Company

Association of Edison Illuminating Companies

Load Research Workshop

San Antonio, TX

February 25-27, 2008

PG&E's Smart AC Pilot Program

- Residential Load Control Program
- Two adaptive controls under test
  - Thermostat re-set
    - Two adaptive re-set strategies
  - Duty cycle control
    - 1 adaptive control strategy
- Enrollment began Spring 07 in Stockton area
  - ~3,000 enrolled in time for Summer 07 sample
  - ~50,000 enrolled as of Jan 08
  - 400,000 targeted by 2010

Program Overview

First Deployed in Stockton, California

- Population
  - 290,000
  - 690,000 in the MSA
- Fourth largest inland city (behind Fresno, Sacramento, and Bakersfield)
- It gets hot...

Program Overview
Incentive to Participate

May Bill Insert

Program Overview
Choice of Devices

- SmartAC PCT

  (Programmable Communicating Thermostat)

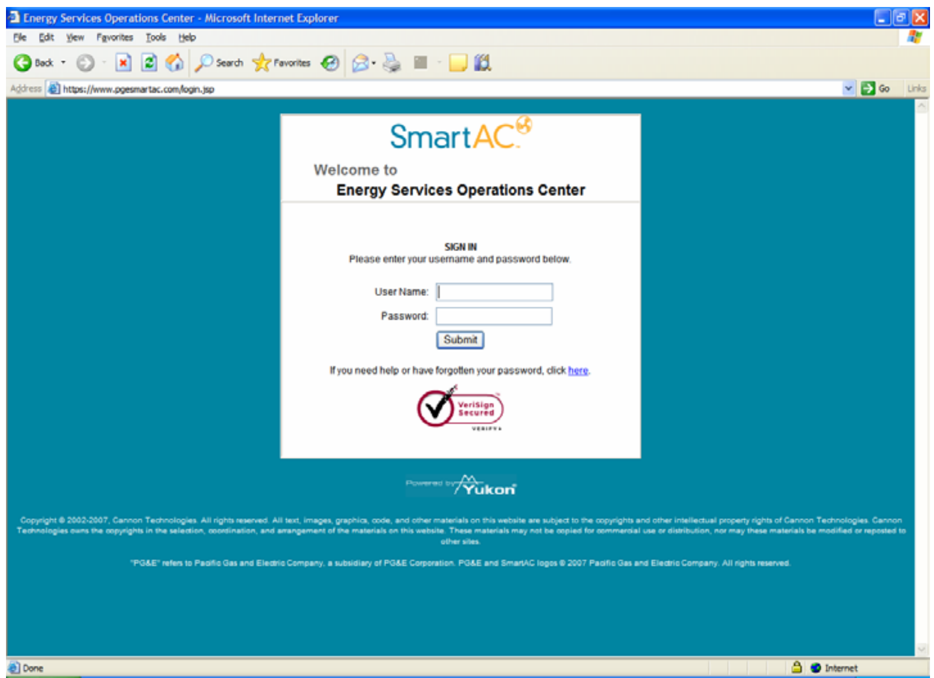
  – Replaces existing thermostat, *requires customer presence to install*

- SmartAC Switch
  – Installed on the AC unit, *does not require access to customer's home*

Program Overview

Log-in or Call to Opt-Out

- In order to opt-out of the event, customers have to log-in or call



Program Overview

What do customers sign up for?

- Per the approved tariff:
  - No more than 100 hours per year
  - No more than 6 hours at a time
  - No more than 4 degrees set-back (for PCTs)

The EM&V Plan

Incentive to Participate in the Sample

- $110
  - – In addition to the $25 to sign-up for the program
  - – In 2007: $80 for the three surveys and the metering
  - – In 2008: $30 for the metering

What's Adaptive about the Control?

- Thermostat re-set
  - Increase temperature in several steps over 2 to 6 hours
  - Allows fans to keep running, avoids clamminess
- Duty cycle switches
  - Device estimates natural duty cycle based on "learning days" signalled by the program
  - During control period, AC unit is limited to 50% (or other specified fraction) of its estimated natural duty cycle

Evaluation Goals

- Impacts
  - Accurate estimates of demand reduction as a function of temperature, time of event, event duration and unit size
  - The temperature sensitivity of demand reduction and connected load
  - Effects of customer behavior, override, signal/switch failure, attrition and snapback
- Process evaluation also conducted
  - Customer decisionmaking, satisfaction, behavior
  - Operational effectiveness

Interval Metering Data Collected

- Duty Cycle Switches
  - Instantaneous kW at 1-minute intervals
  - 182 units
- Tstats
  - Avg kW at 15-min intervals
    - Average of 15 1-minute instantaneous observations recorded on logger
    - 86 units
  - Instantaneous kW at 1-minute intervals
    - 84 units

Metering Sample

Stratum	Type Of Device	Total Tons From All Units	Multiple AC units on site (1=Yes)	Program Participants as of 06/11/2007	Percent of Total Population by Device Type	Number of Metered Homes	Number of Metered AC Units
1	PCT	<4	0	483	72%	88	90
3	PCT	>=4	0	148	22%	39	39
4	PCT		1	40	6%	19	41
5	Switch	<4	0	1404	64%	72	73
7	Switch	>=4	0	637	29%	53	53
8	Switch		1	144	7%	26	56
Totals*				2856		297	352

*Original sample participant count was determined by when the file was created, June 11th, 2007.

Thermostat Analysis

Past Work—Thermostat re-set

- Model kW as function of cooling degree-days CDD
  - CDD base temperature estimated by the regression
- Re-set effect is like shifting the CDD base up

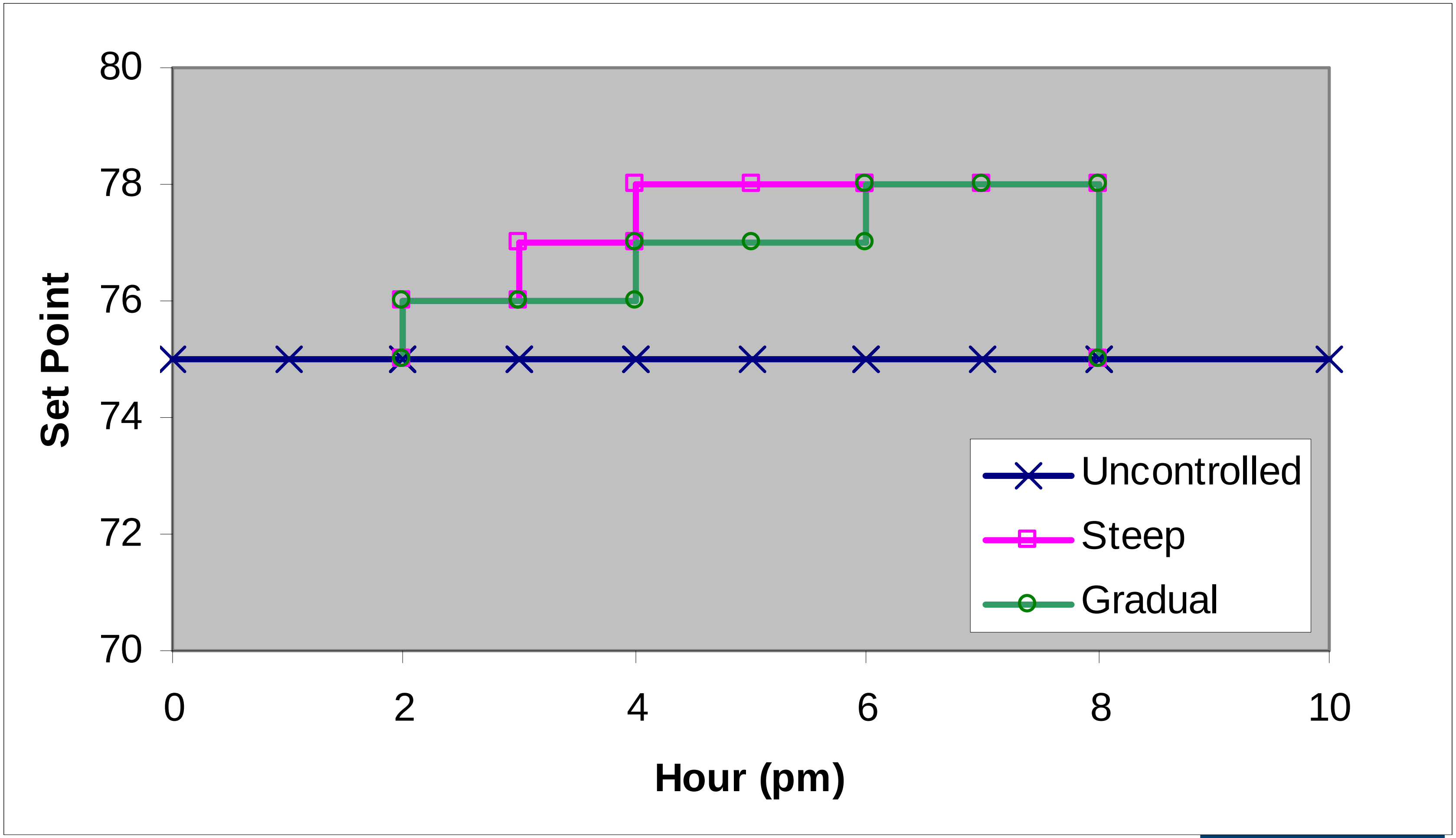
- Observed savings
  - (Modeled uncontrolled kW) – (Observed kW)

- Projected savings
  - (Modeled uncontrolled kW) – (Modeled re-set kW)

New Wrinkles--Thermostats

- Re-Set amount changes over the control period
  →Have to model by time since start of control as well as time of day
  – Two different ramp-up patterns tested each control day
- In practice all test periods started at 2 pm
  – Some didn't finish the ramp-up period

Steep and Gradual Set-Point Ramp



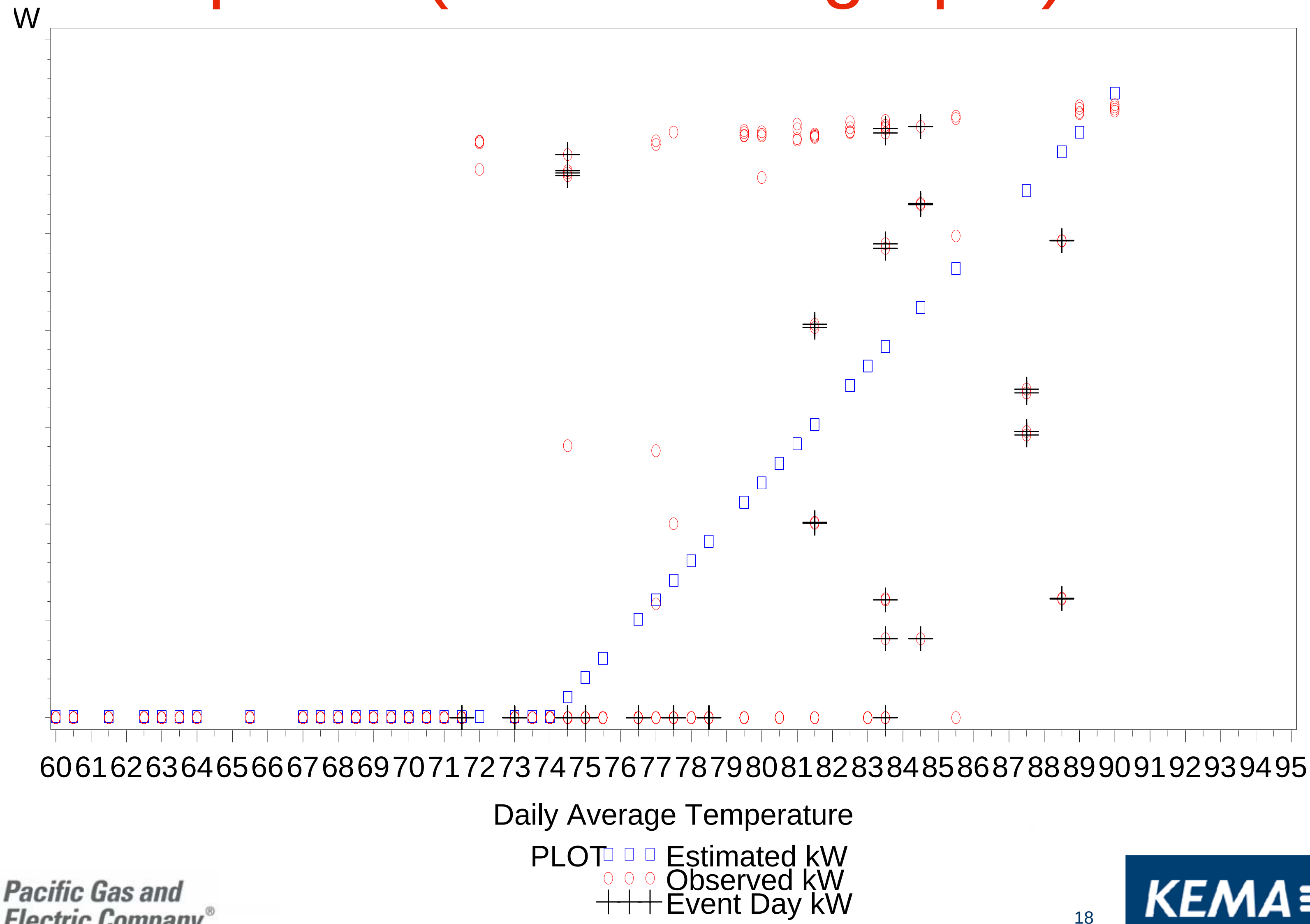
Thermostat model

- Uncontrolled load model
  - $L_{jdh} = \alpha_{jh} + \beta_{jh} C_{dh}(\tau_j) + u_{jdh}$

  - L_{jdh} = load for unit j day d hour h
  - $C_{dh}(\tau_j)$ = cooling degree-days day d, base τ_j
    $= (Temp - \tau_j)$ if $Temp \geq \tau_j$
    $= 0$ if $Temp \leq \tau_j$
  - u_{jdh} = random error
  - α_{jh} β_{jh} τ_j = coefficients estimated by regression

- Fit over non-controlled days

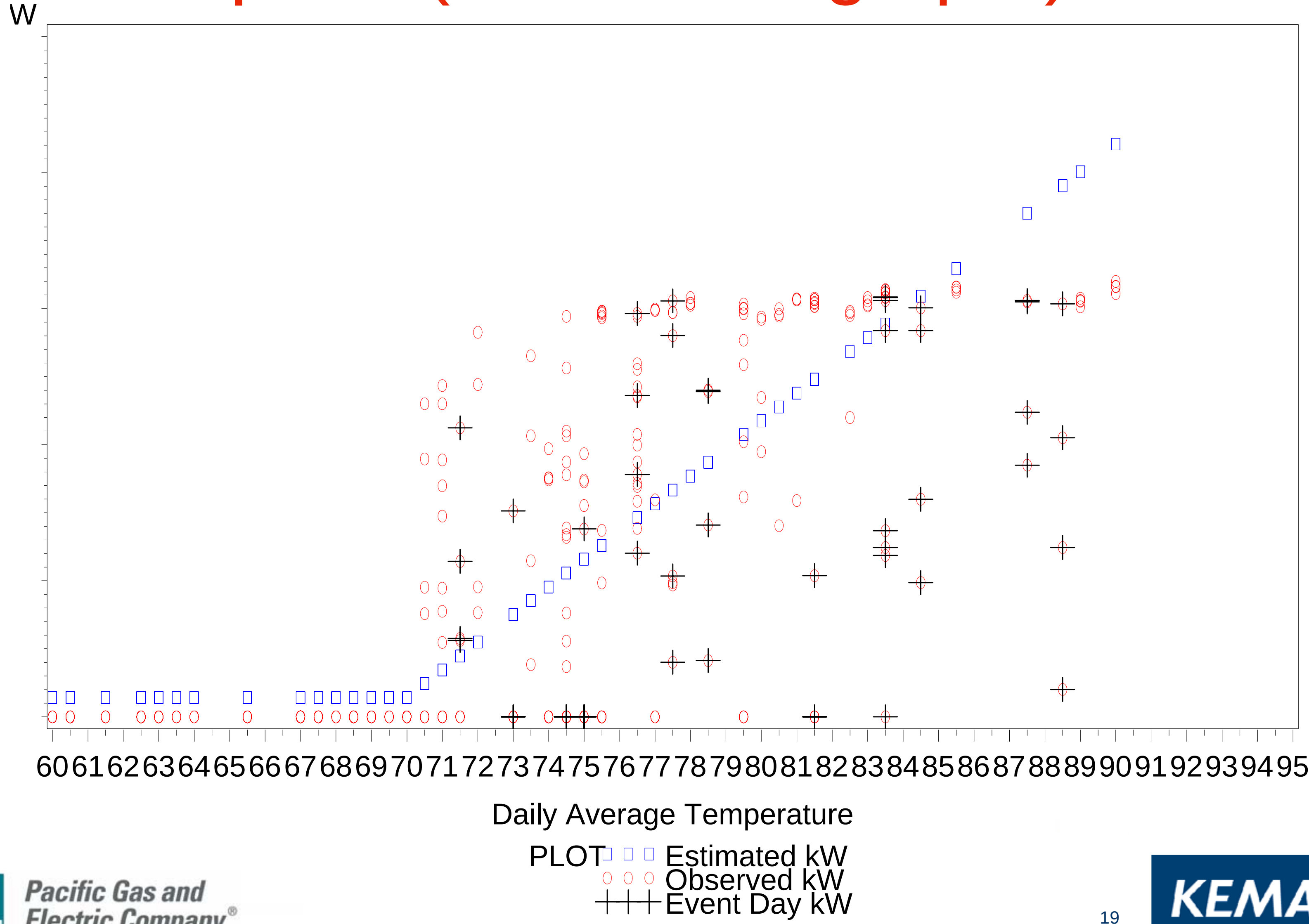
Example 1 (hour ending 4pm)



Pacific Gas and Electric Company®

KEMA

Example 2 (hour ending 4pm)



Pacific Gas and Electric Company®

KEMA

Thermostat Model Estimates

- Estimated load without reset
  - $L^{\wedge}_{jdh} = \alpha^{\wedge}_{jh} + \beta^{\wedge}_{jh} C_{dh}(\tau_j^{\wedge})$

- Estimated load at r degrees tstat re-set

  $L^{\wedge +}_{jdh} = \alpha^{\wedge}_{jh} + \beta^{\wedge}_{jh} C_{dh}(\tau^{\wedge}_j + r)$

Thermostat Savings

- Observed savings
  - Estimated uncontrolled load minus observed load
  - $S_{jdh} = L^{\wedge}_{jdh} - L_{jdh}$

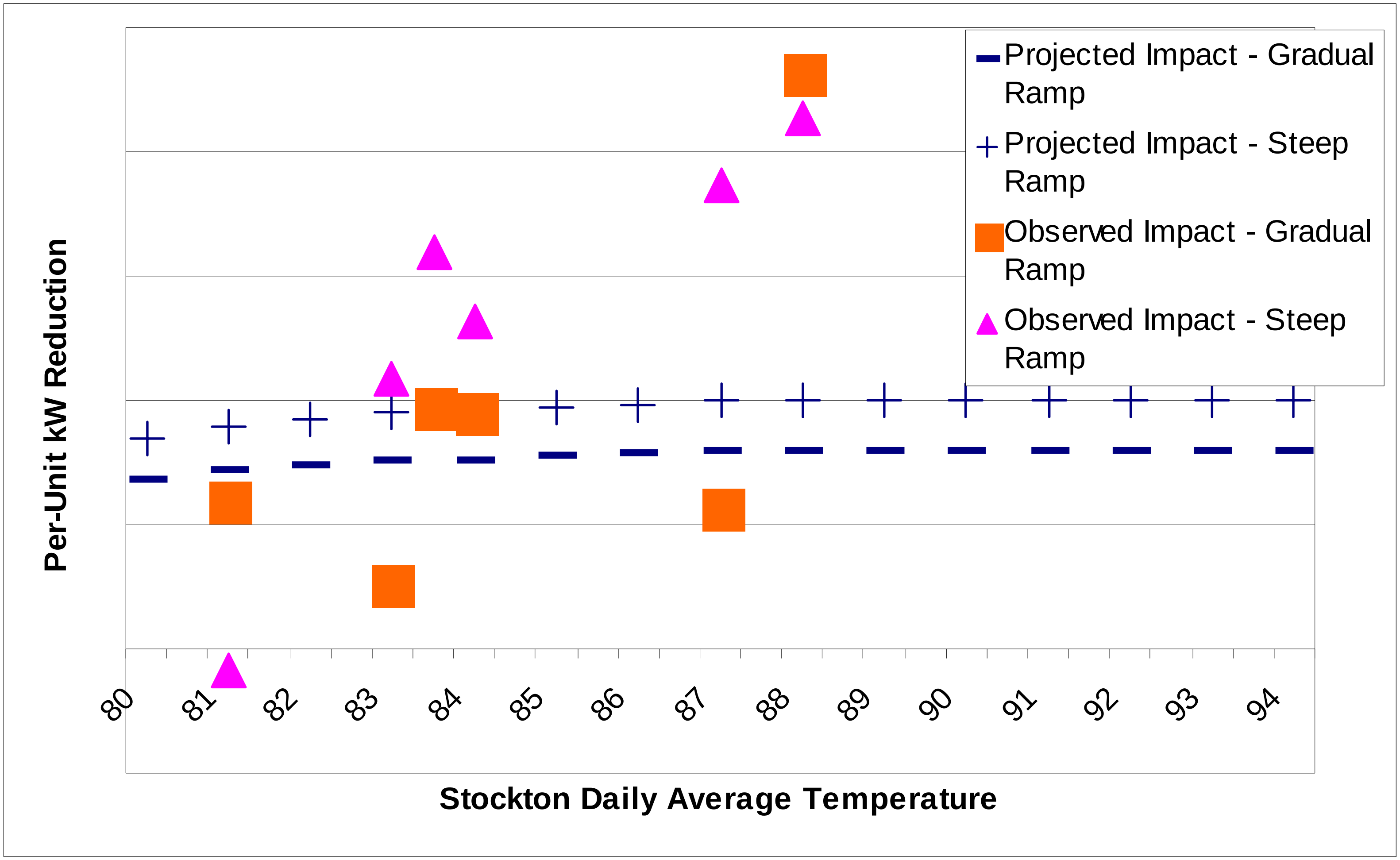
- Projected Savings
  - Estimated uncontrolled load minus estimated load with r degrees re-set
  - $S_{jdh}^{\sim} = L^{\wedge}_{jdh} - L^{\wedge +}_{jdh}$

    $= \beta^{\wedge}_{jh} [C_{dh}(\tau^{\wedge}_{j}) - C_{dh}(\tau^{\wedge}_{j} + r)]$
  - $S_{jdh}^{\sim} = \beta^{\wedge}_{jh}\, r$ (if $Temp_d > \tau^{\wedge}_{j} + r$)

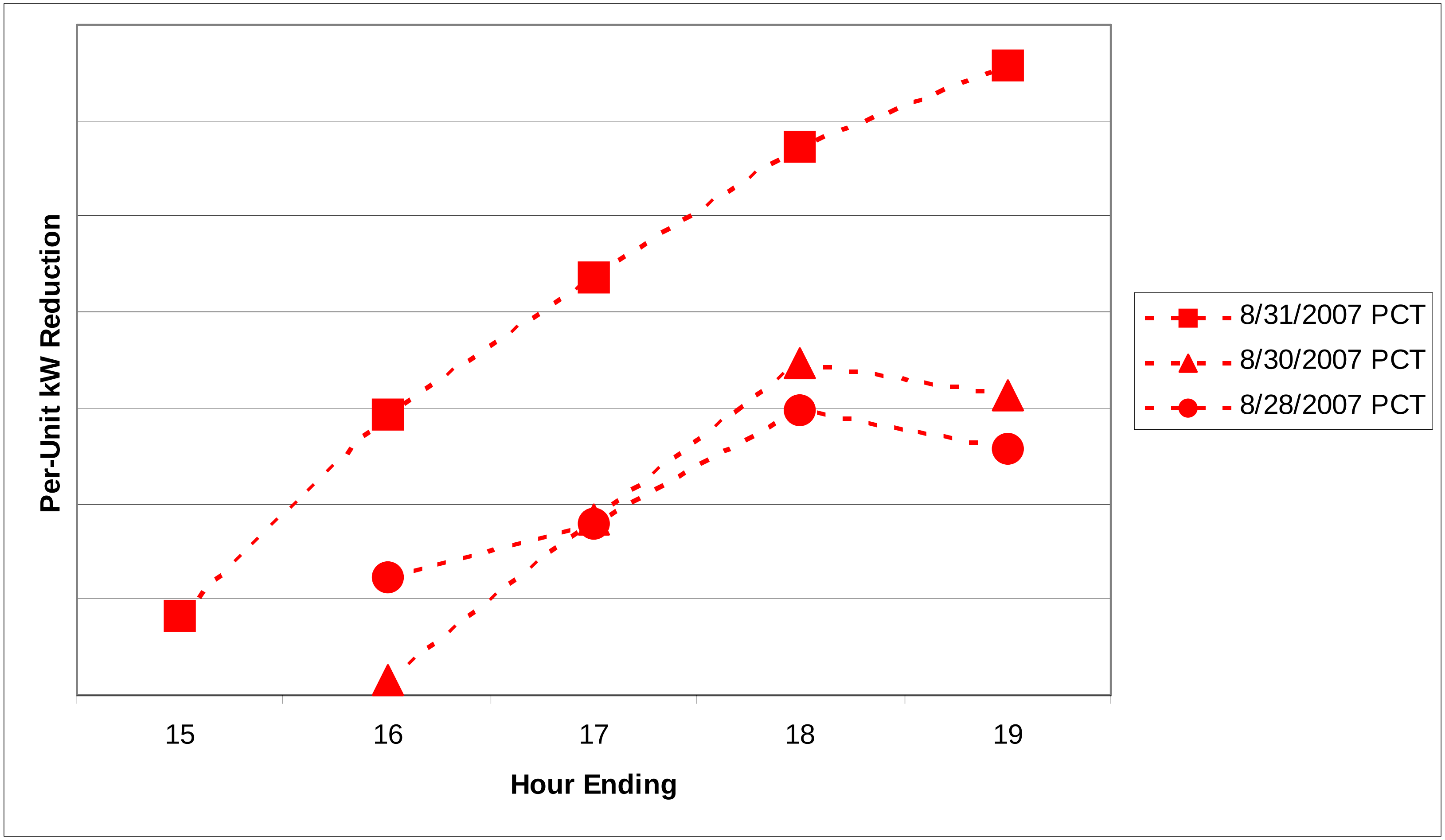
Pacific Gas and Electric Company®

KEMA

Observed and Projected Impacts



Impact Illustration, Hot Days, Tstat



Pacific Gas and Electric Company®

KEMA

Duty Cycle Switch Meter Analysis

Past Work—Duty Cycle Control

- Fixed Duty Cycle limit (eg., 50%)
- Tobit model of duty cycle (% time running) as function of outside temperature
  - Recognizes duty cycle always between 0 and 1

- Savings based on
  - Probability natural DC > 50%
  - Average natural DC when it is above 50%
  - Assumed limit to 50% during control period
  - kW draw when running (connected load, installed capacity)

New Wrinkles—DC Control Switches

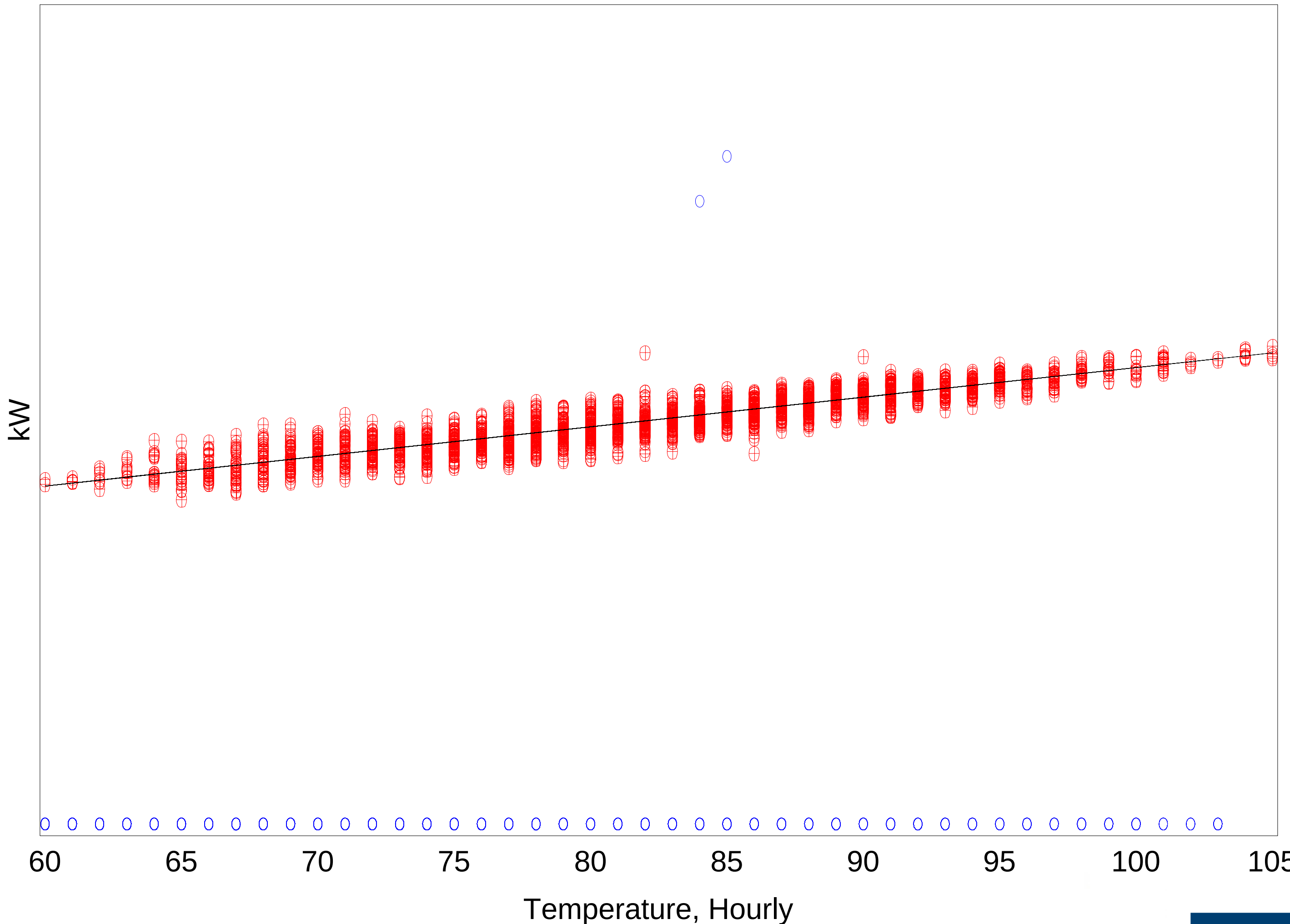
- Duty cycle limit depends on device's estimate of natural duty cycle
- Device's estimate of natural duty cycle varies over the summer
- Device's estimate is unknown
  - No 2-way communication
  - Algorithm details proprietary

2 Models Fit for Each AC Unit

1. Connected load vs *hourly* outside temperature
   - Power draw when unit is on increases with current ambient temperature
2. Duty cycle (runtime %) vs *daily* outside temperature (& possibly lagged temperature & humidity)
   - Cooling provided is essentially a function of runtime
   - Cooling demand increases with temperature
   - Relation to temp not instantaneous
     - house structure retains heat/cold

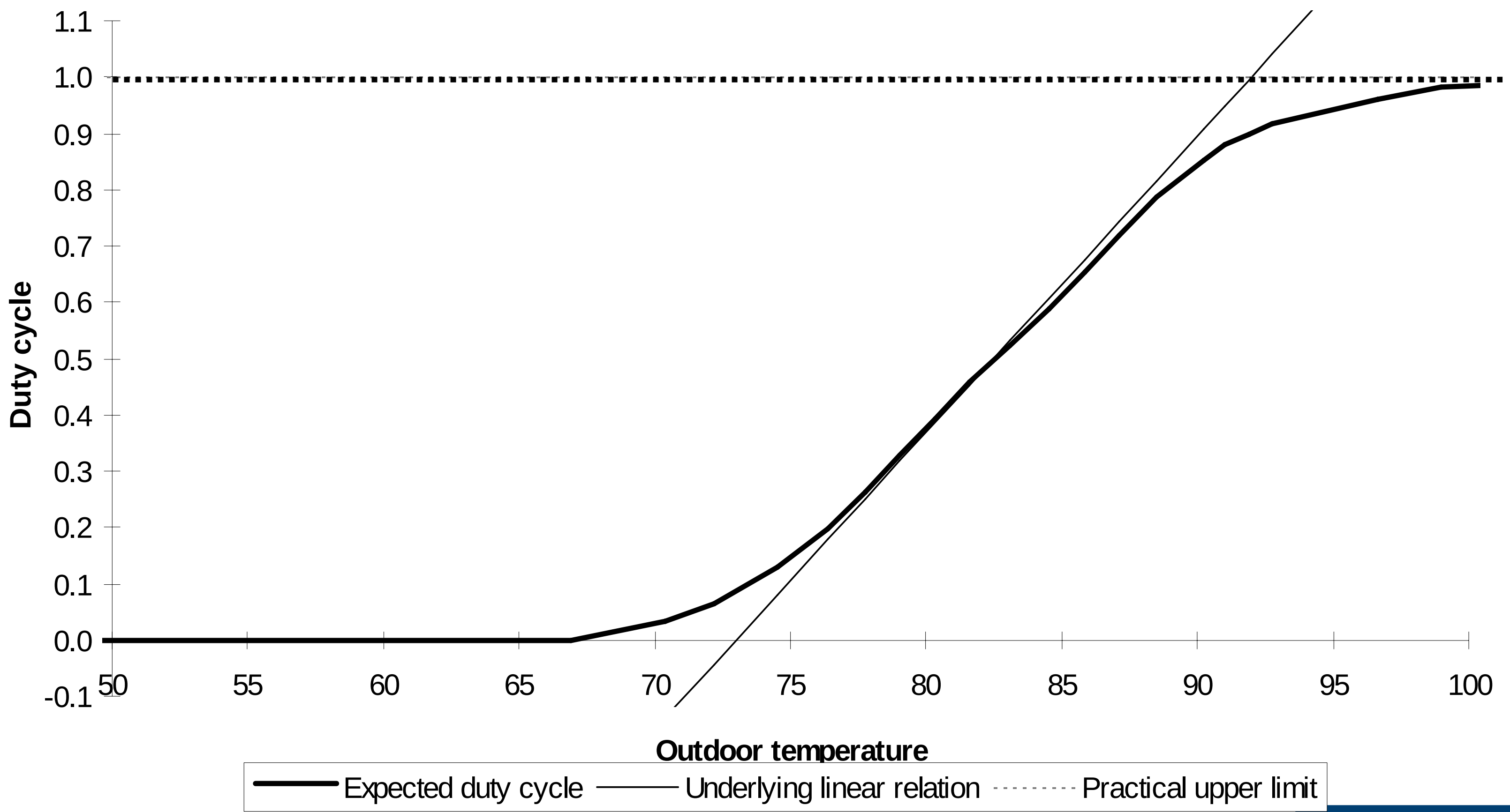
- Use interval data to estimate both models

Connect Load by Hourly Temperature



Duty Cycle vs Outdoor Temperature

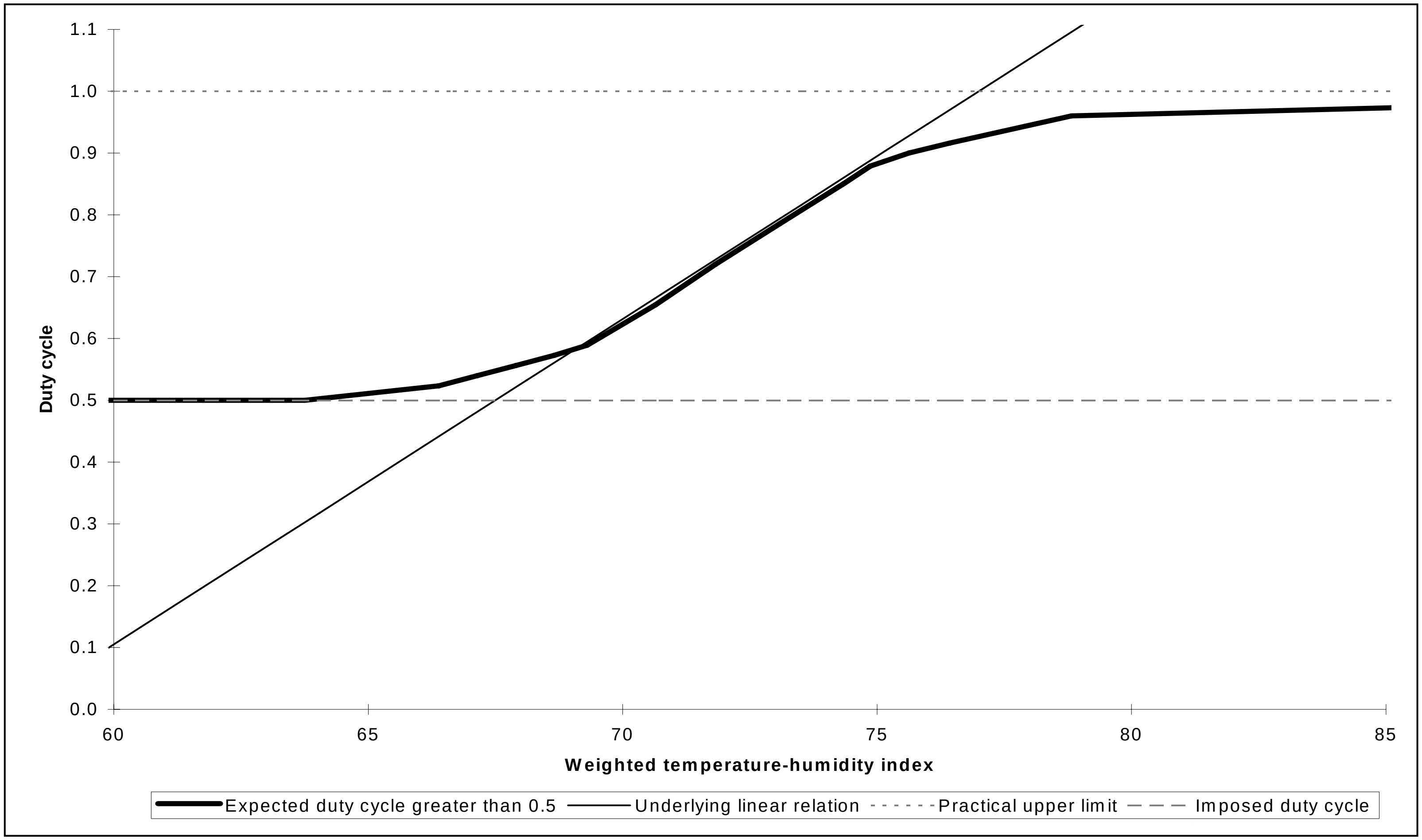
Underlying linear relation constrained to [0, 1]



Pacific Gas and Electric Company®

KEMA

Expected Duty Cycle if >50%



Pacific Gas and Electric Company®

KEMA

Tobit Model (separate fit each unit)

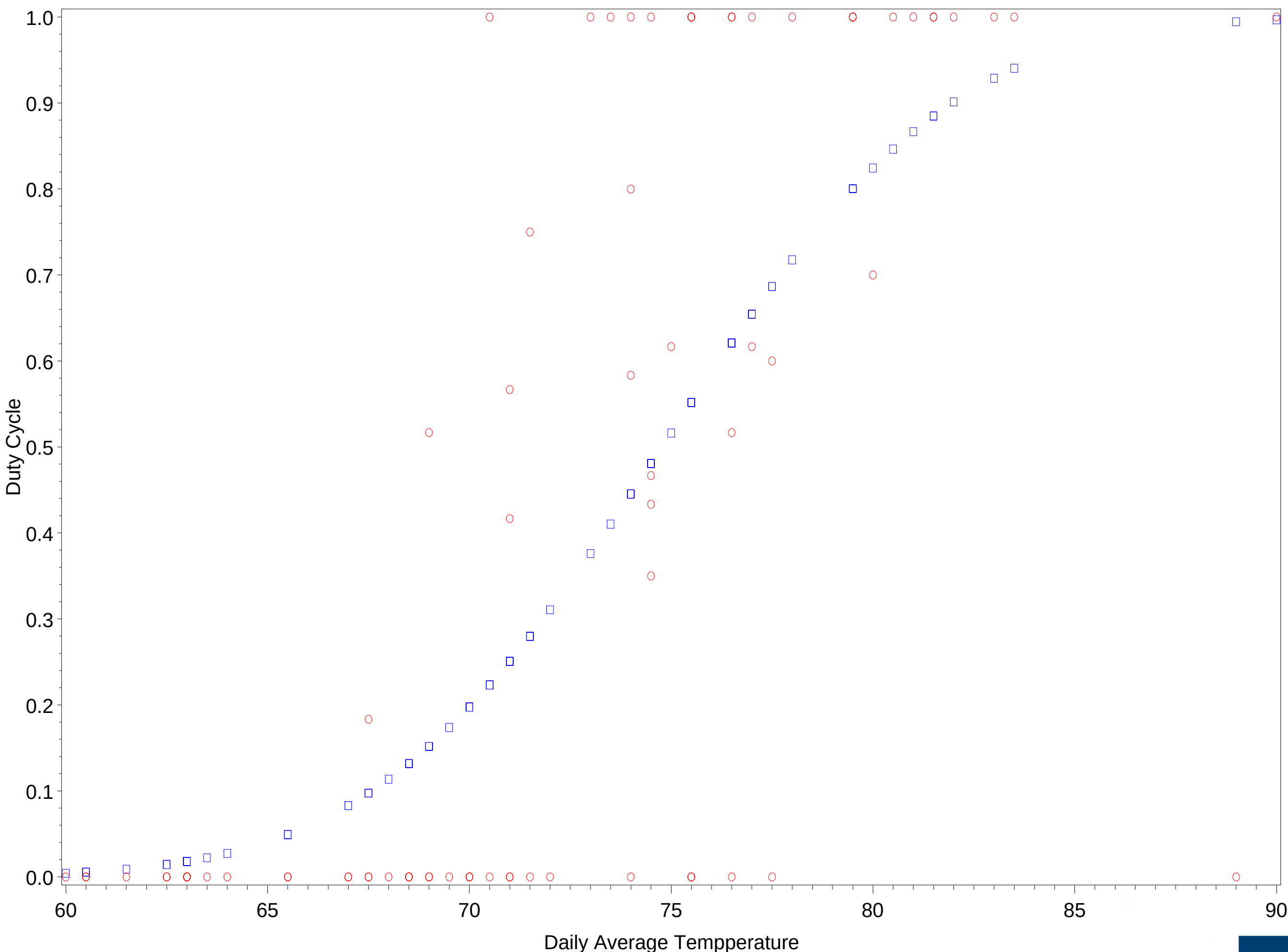
- Underlying linear model of unconstrained duty cycle, with random error *u* (normally distributed)

$$DC^*_{dh} = a_h + b_h Temp_d + u_{dh}$$

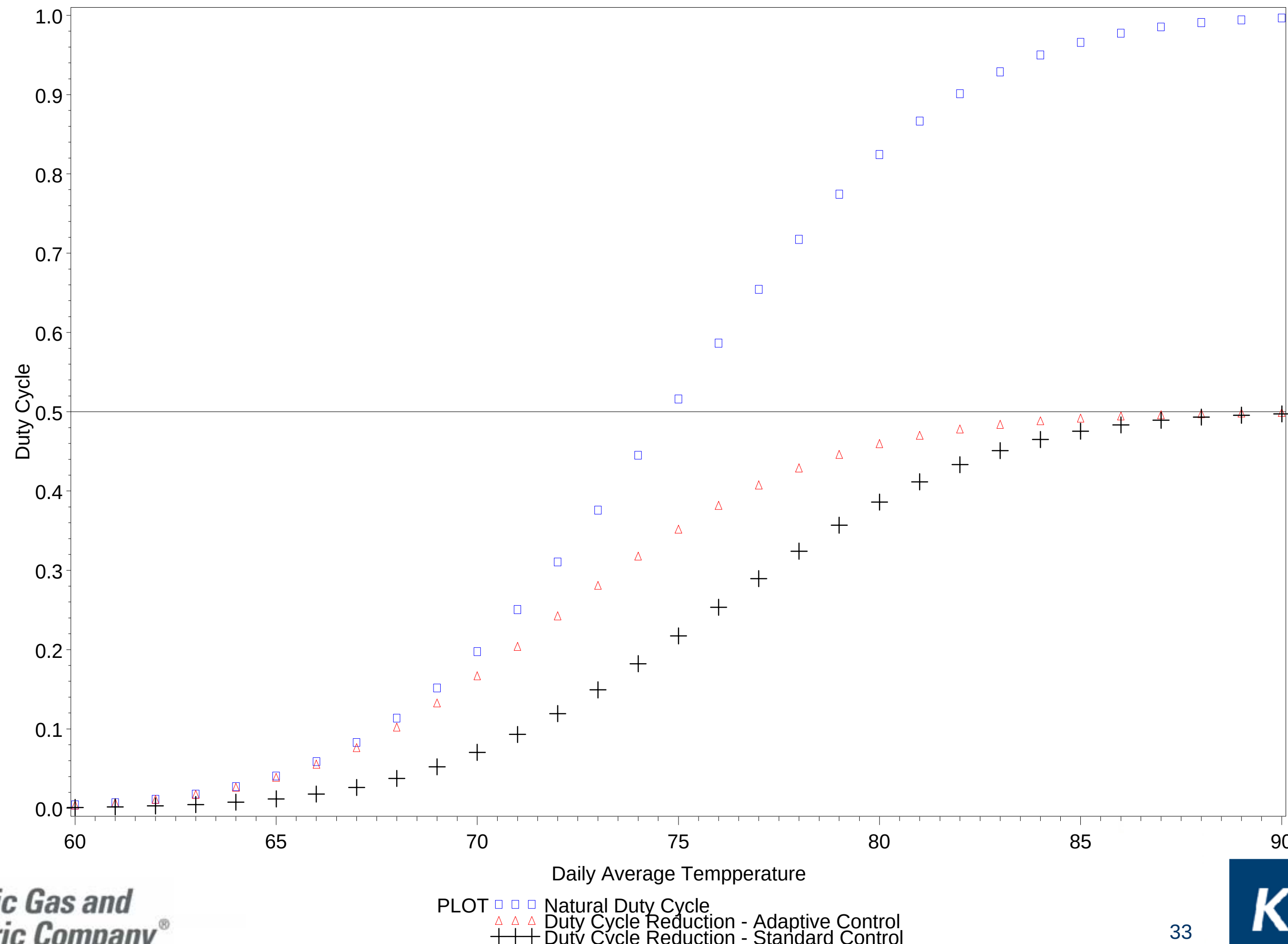
- Observed duty cycle day *d*, hour *h*

$$DC_{dh} = \begin{cases} 0, DC^*_{dh} \le 0 \\ 1, DC^*_{dh} \ge 1 \\ DC^*_{dh} 0 < DC^*_{dh} < 1 \end{cases}$$

Example: Fitted Tobit Model



Expected Duty Cycle w/ Reductions using Adaptive and Standard 50% controls



Pacific Gas and Electric Company®

Duty Cycle Effects for each unit

Fixed Duty Cycle Limit = 50%

- Probability uncontrolled DC would exceed 0.5:
  $Pr(DC > 0.5)$

- Expected uncontrolled duty cycle if above 0.5:
  $E(DC|DC > 0.5)$

- Modeled DC reduction, given hour of the day, daily temp
  $$\Delta DC^{\sim} = Pr(DC > 0.5) \times [E(DC|DC > 0.5) - 0.5]$$
- Observed duty cycle reduction
  $\Delta DC = E(DC) - DC_{obs}$

Pacific Gas and Electric Company®

KEMA

Duty Cycle Effects for each unit

Adaptive Control

- From Tobit, for a given hour of the day, daily temp
  - Estimated natural duty cycle DC_0
  - Estimated controlled duty cycle limit $.5DC_0$
  - Probability uncontrolled DC would exceed $0.5DC_0$: $Pr(DC > 0.5DC_0)$
  - Expected uncontrolled duty cycle if above $0.5DC_0$: $E(DC|DC > 0.5DC_0)$

Duty cycle reductions for each unit

Adaptive Control

- Modeled duty cycle reduction

$$\Delta DC\sim = Pr(DC > 0.5DC_0) \times [E(DC|DC > 0.5DC_0) - 0.5DC_0]$$

  – *Function of daily temp and hour of day*

- Observed duty cycle reduction

$$\Delta DC = E(DC) - DC_{obs}$$

  – *Function of daily temp, hour of day, actual DC_{obs}*

Savings for each DC controlled unit

- From Tobit Analysis
  - Modeled duty cycle reduction $\Delta DC\sim$
  - Observed duty cycle reduction ΔDC
- From Connected Load model: $kW_{installed}$
  - *Function of hourly temp*
- Modeled savings for a given day and hour
  - $S^{\sim} = \Delta DC\sim \times kW_{installed}$
- Observed savings for a given day and hour
  - $S = \Delta DC \times kW_{installed}$

BUT limit DC_{cap} set by device is unknown

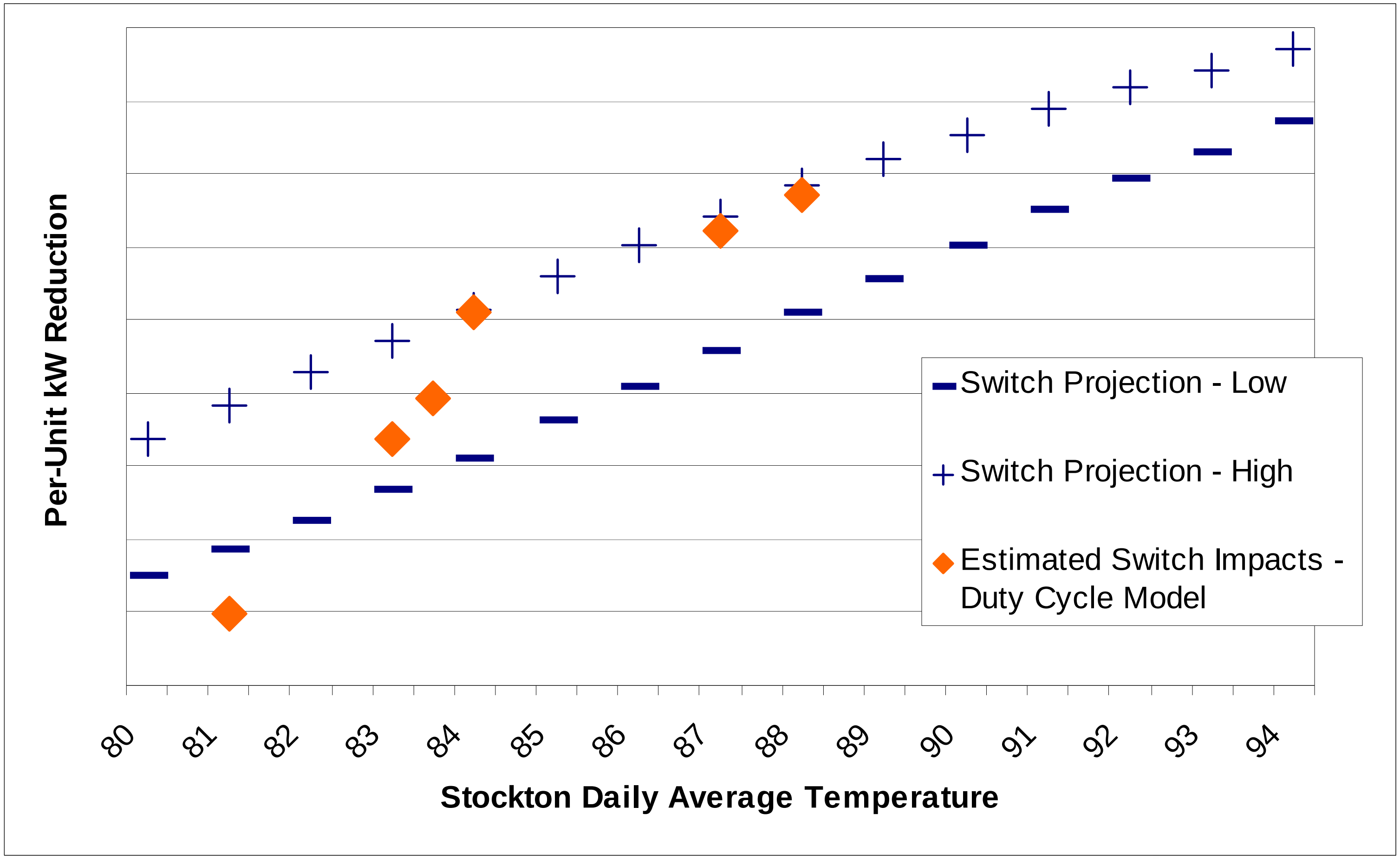
- Modeled duty cycle reduction

$$\Delta DC\sim = \Pr(DC > DC_{cap}) \times [E(DC|DC > DC_{cap}) - DC_{cap}]$$

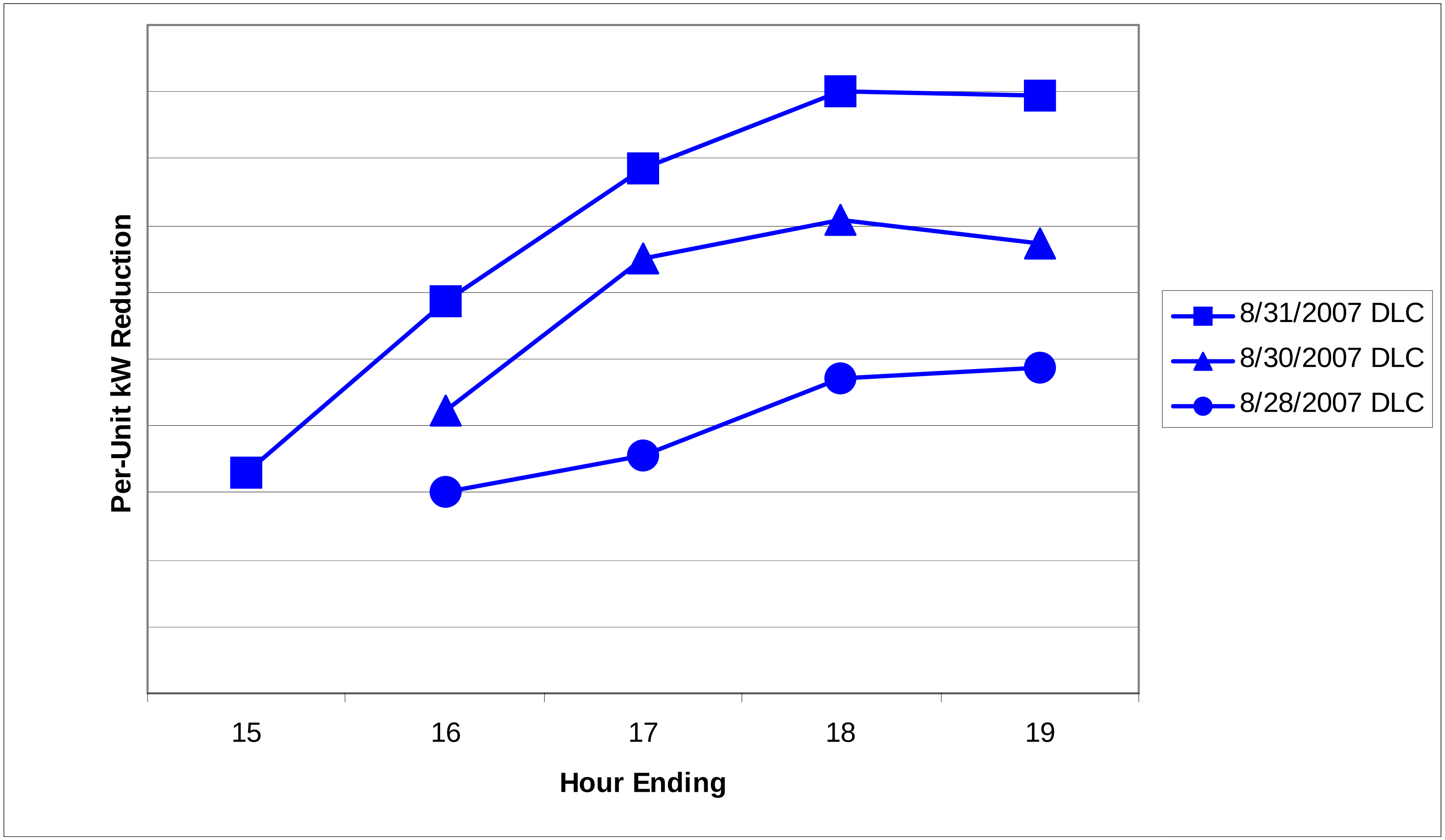
- High estimate
  – Assume device estimate matches our weather model's

- Low estimate
  – Assume device estimate is DC0 = 1
  → DC_{cap} set at .5, = highest possible

Observed & Projected DC Savings



Impact Illustration, Hot Days, Switch



Putting the Pieces Together

Ratio Expansion as Cluster Analysis

- Savings per ton
  - $R_{hd} = \Sigma_k \Sigma_c \Sigma_j \, w_{kcj} \, S_{kcidh} \, / \, w_{kcj} \, T_j$
  - $S_{TOThd} = T_{TOT} \, R_{hd}$

- for unit j of customer c in stratum k
  - w_{kcj} = expansion weight
  - S_{jdh} = savings for day d hour h
  - T_{kcj} = tons
- $w_{kcj} = (N_k/n_k)(M_{kc}/m_{kc})$
  - N_k, n_k = Pop, sample customer counts, stratum k
  - M_{kc}, m_{kc} = Pop, sample unit counts, customer kc

Methods Lessons—Thermostat Re-Set

- Observed savings vary from projected using kW model
- Greater variability of impact may be inherent in the type of control vs DC or standard 1-step re-set
  - Re-Set has little effect on a hot day if the unit is maxed out
  - Effect of gradual re-set more complex and varied across homes and weather conditions
- Possible improvements in projection accuracy
  - account for lag effects more explicitly to estimate impacts in each hour of ramped control?
  - use Tobit model?

Methods Lessons—Adaptive Switches

- Tobit model works well
  - Projected savings derived directly from the model
  - Observed and projected savings align well for control periods after some “learning days”
  - May get some improvement if could incorporate exact algorithm used by device to set duty cycle cap

Next Steps

- Program expanded to 2 other areas for 2008
- Expanded metering sample sizes to provide greater accuracy and segmentation opportunities

Questions?