Maximizing the Benefits of Residential Pre-Cooling

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ABSTRACT

Residential air conditioning represents a challenging load for many electric utilities due to poor load factors. This is most pronounced in hot-dry climates where nighttime cooling loads are often minimal due to a lack of humidity, but loads in the late afternoon are high. Building mechanical pre-cooling is a strategy that improves the load factor by shifting cooling operation from on-peak hours to off-peak hours. Shifting air conditioner use to off-peak periods provides benefits to utilities and the electric grid, as well as to occupants who can take advantage of time of use electric rates. The paper presents results of EnergyPlus modeling to evaluate pre-cooling in hot-dry climates. Field monitoring results are also presented, obtained from a high performance home which utilizes the slab floor mass as thermal storage. A successful off-peak air conditioning strategy offers the potential for increased efficiency, assured occupant comfort, and a more reliable and robust electrical grid. The advent of demand response capabilities and further integration with PV time-of-use generation patterns provides for additional opportunities to flatten loads and optimize grid impacts.

Introduction

Air conditioners are present in nearly all newly built production homes throughout the U.S. and some form of mechanical air conditioning equipment is found in 87% of all homes, based on the 2009 RECS survey (EIA, 2009). According to DOE's 2009 Residential Energy Consumption Survey data, cooling represents about 6% of annual residential site energy consumption nationally[1], but the impact on utility peak demand is much more significant. This is especially true in hot-dry climates such as California where residential cooling loads are more concentrated around the hottest hours of the day. In fact, California residential air conditioning represents about 15% of the state's peak coincident electrical demand, but only 2% of annual electrical consumption (Brown and Koomey, 2002)[2]. Improving cooling efficiency, as well as its impact on the electrical grid, is clearly an important national objective and a key part of ongoing Smart Grid efforts.

In its simplest form, pre-cooling can be realized by scheduling air conditioner operation to reduce setpoints 2 to 6°F below typical settings in advance of the utility on-peak time period. Performance benefits stem from reducing compressor cycling degradation and operating the vapor compression equipment at outdoor temperatures lower than would occur during the on-peak time window. These benefits are counteracted by the imperfect nature of pre-cooling,

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[1] 0.635 quads out of a total 10.183 quads of residential consumption annually.

[2] Commercial building air conditioning in California represents about 5% of statewide consumption, but a slightly lower 14% of coincident peak demand. The resulting load factor for commercial cooling is therefore nearly three times higher than for the residential sector.

particularly in homes which have insufficient thermal storage capacity, which may result in overcooling on milder days, and greater envelope losses due to lower indoor temperatures.

Although considerable work has been completed in commercial building pre-cooling over the past several decades (Xu et al, 2004; Smith and Braun, 2003), research efforts in the residential space are much more limited. This may be due to the assumption that larger commercial buildings represent a bigger opportunity for engagement, as opposed to the more diffuse characteristics of individual residential customers. Findings from several more recent residential studies are described below.

Ventilation and air conditioner pre-cooling strategies were evaluated for the Sacramento Municipal Utility District in new homes under the Off-Peak Over-Cooling Project (Springer, 2007). Detailed modeling using DOE-2 indicated that a strategy that combined air-conditioner pre-cooling with nighttime ventilation cooling strategy generated favorable energy and demand performance with an annual cooling energy savings of 24% projected for typical Sacramento, CA new construction homes. Field monitoring at one test home showed impressive diversified demand savings of 88% within the 5 to 8 PM summer "super" peak period, although annual cooling energy use was 26% greater with pre-cooling.

A 2007 Pacific Gas & Electric (PG&E) study monitored nighttime ventilation cooling in six homes, also near Sacramento, CA (Matrix, 2007). The six homes were monitored over the summer in alternating modes: baseline mode with ventilation cooling disabled, and a pre-cooling mode that combined nighttime ventilation pre-cooling with daytime air conditioning. Two different ventilation cooling systems were tested. Both system types were shown to be effective at reducing Noon to 6 PM electrical consumption (48 to 50% reduction), although annual cooling energy was estimated to increase by 2 to 17%, depending upon the type of ventilation cooling system[3]. The more efficient ventilation of the two ventilation cooling systems has since had control updates completed to minimize unnecessary pre-cooling on milder days.

Objectives

The primary focus of the research described here seeks to identify best practice setpoint strategies for air conditioner pre-cooling in hot-dry climate homes. The evaluation approach applied a combination of EnergyPlus simulation modeling and field monitoring to quantify energy and demand savings. Key factors explored in this study include house "efficiency" characteristics (thermal mass, envelope and HVAC thermal performance, and infiltration rates), climate impacts, and utility rates.

Model Simulations

Approach

Over the 2013 summer, four existing Sacramento, California area homes, ranging in vintage from 1954 to 2005, were monitored with support from the Department of Energy (DOE)

[3] For days with high temperatures exceeding 92°F, annual energy savings relative to the base case were estimated at 14-30%, indicating that mild day over-cooling contributed to the less favorable full season performance.

sponsored Building America program. Constant thermostat setpoint and pre-cooling modes were tested at each of the monitoring sites. Onsite audits collected assembly details and insulation levels, cooling system specifications, whole house infiltration levels, duct leakage, occupancy patterns, and general internal load characteristics. Using the results of monitoring and onsite audits, energy models of each of the homes were developed and calibrated using actual meteorological year (AMY) weather files. The Department of Energy's EnergyPlus v8.1 and the National Renewable Energy Laboratory's BEopt v2.1 whole building simulation tools were utilized. BEopt was relied upon to draw the house geometry and apply most of the building and operational specifications. An EnergyPlus input file was then generated from BEopt and edited externally to adjust additional parameters that could not be adjusted within BEopt, such as occupancy schedules and pre-cooling thermostat schedules.

The calibration step involved comparing daily interior temperature and cooling system operating profiles as well as total delivered cooling energy to the homes. To align the modeling results with those from monitoring, adjustments were made to certain envelope characteristics if their precise qualities were not known (i.e. window solar heat gain coefficient). The other adjustment that was made was to EnergyPlus' Temperature Capacity Multiplier object, which controls the effective thermal storage capacity of the zone. It was found that if this was kept at the default value of 1.0 the model reacted much too quickly to outdoor environmental changes and internal heat gains.

A generalized model was developed to estimate peak demand and energy savings under different scenarios including additional setback schedules, climates, and utility rate structures. A 2,150 ft^2 two-story single family home was modeled with 15% window-to-exterior wall area, slab on grade construction, and a vented attic. Two general building types were evaluated. The first is a new home with envelope characteristics that are similar to the Building America Benchmark house as defined by the House Simulation Protocols (HSP) (Wilson et al. 2014). The Benchmark house is roughly equivalent in performance to a home built to 2009 IECC standards and to a 2005 vintage California Title-24 code home. The second building type is an improved design with source energy use that is 25-30% lower than the Benchmark house. Table 1 lists the general characteristics of the two models. Building operation schedules are all based on the HSP with the exception of cooling thermostat setpoints. Applying the calibration methods described above, a revised Temperature Capacity Multiplier of 15 was also applied.

Since the focus of this research is on hot-dry climates, Sacramento and Phoenix were selected to be representative of the major hot-dry space cooling regions in the United States. Phoenix is in the International Energy Conservation Code (IECC) climate zone 2B and Sacramento is in 3B. TMY3 weather files were used in the simulations.

Table 1. Building characteristics applied in the energy model

Building characteristic	Benchmark home	High performance home
Walls	2x4 R-13	2x6 R-21 + R-5 exterior foam
Roof/Attic	R-30 vented attic	R-49 vented attic w/ radiant barrier
Windows	0.37 U-value, 0.30 SHGC	0.29 U-value, 0.26 SHGC
Floor	Uninsulated slab-on-grade	Uninsulated slab-on-grade
Infiltration	7 ACH_{50}	2 ACH_{50}
Thermal Mass	80% carpeting, ½" drywall all walls & ceilings	100% Exposed slab 1st floor, 5/8" drywall all walls & ceilings
Cooling system	SEER 13 split system, 0.5 W/cfm fan efficacy	SEER 15 split system, 0.5 W/cfm fan efficacy
Ductwork	R-8, 15% leakage in attic	In conditioned space

Table 2 describes the pre-cooling setpoint controls that were evaluated. Two 4-hour pre-cooling time periods were selected: 1) cool morning hours that straddle the outdoor daily minimum temperature, optimizing system operating efficiencies, and 2) the Noon to 4pm period immediately preceding the 4pm-7pm peak period, as defined in this research.

Table 2. Setpoint control strategies evaluated in the energy model

Case	Description
Basecase	Constant setpoint of 76°F
Morning Pre-Cool	-Vary setback from 74°F to 70°F in 1°F increments -Time setback: 4am-8am, 5am-8am, 6am-8am -Evaluate setup to 78°F from 3pm-8pm
Part Peak Pre-Cool	-Vary setback from 74°F to 70°F in 1°F increments -Time setback: 12pm-4pm, 1pm-4pm, 2pm-4pm -Evaluate setup to 78°F from 4pm-8pm

Understanding that optimal pre-cooling strategies may differ on days with different cooling demands, three categories of "cooling severity" were defined. These are listed in Table 3 for the two climates evaluated:

Table 3. Daily outdoor temperature grouping for evaluation

	Daily Average Outdoor Air Temperature (°F)		
	Group 1	Group 2	Group 3
Sacramento	< 70°F	70°F - 80°F	> 80°F
Phoenix	< 85°F	85°F - 95°F	> 95°F

Two utility rate structures were defined for this study: a time-of-use (TOU) tariff was evaluated for both climates zones and a real time pricing (RTP) rate was investigated for Sacramento, CA only. The TOU tariff is based on a 3 hour peak period 4pm-7pm during which time the price for electricity is assumed to be three times the base rate of $0.11/kWh.

RTP tariffs are highly variable across regions and utilities. The authors developed a theoretical RTP tariff to evaluate how pricing electricity on an hourly basis dependent on demand and utility load shapes affects pre-cooling's impact in a hot-dry climate similar to Sacramento, CA. This tariff is structured around three daily curves, one for each of the three groups of temperature conditions listed in Table 3[4]. Figure 1 graphs the assumed pricing for each set of temperature conditions.

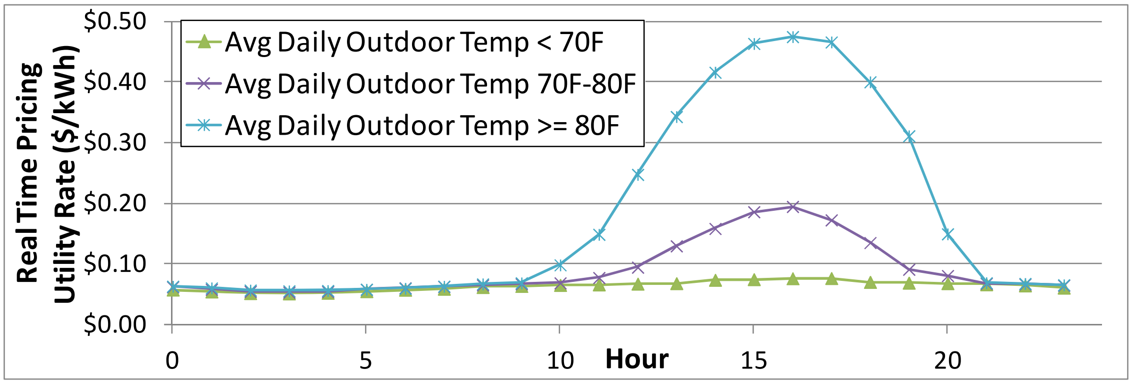

Figure 1. Theoretical real time pricing rate structure based on daily outdoor temperature conditions.

Modeling Results

Figures 2 and 3 present modeling results from the Sacramento simulations for the Benchmark case and the high performance case, respectively. The figures demonstrate the optimal thermostat setpoint strategies which result in the lowest summer 4-7pm peak demand[5] (left) and the lowest annual cooling energy consumption (right). Again, the base case results are for a fixed 76°F setting. The annual energy and cost figures are based on combining the three temperature dependent optimal setpoint strategies over the cooling season and are presented for both a reduced energy and reduced peak demand target.

Generally, deeper and longer setbacks proved to yield better results on hotter peak days compared to milder days. In all cases a setup to 78°F during the peak hours is required to realize energy savings. Cooling energy savings of 15% were estimated in the Benchmark house and 9% in the high performance house. Utility cost savings ranged from 27%-38%, depending upon the rate assumption.

It was not possible in either home to completely eliminate air conditioner operation during peaks hours on the hottest days. However, in the high performance home a pre-peak setback of at least 3°F significantly reduced cooling energy use during peak hours by greater than 90% (even without the 78°F setup), although this comes with a penalty of as much as 40% increased cooling energy use. The approach that minimizes peak demand increases energy use by

[4] The shapes of the three curves are based on the California Energy Commission's Time Dependent Valuation (TDV) hourly multipliers for Climate Zone 12 (Sacramento) and have no relation to actual utility tariffs. Averages were taken for each of the three daily temperature bins.
[5] Maximum peak cooling demand for the outdoor temperature bin is plotted.

14%-16%. For both house types the optimal strategies serve both the utility in terms of reduced peak demand and the homeowner in terms of lower annual utility costs.

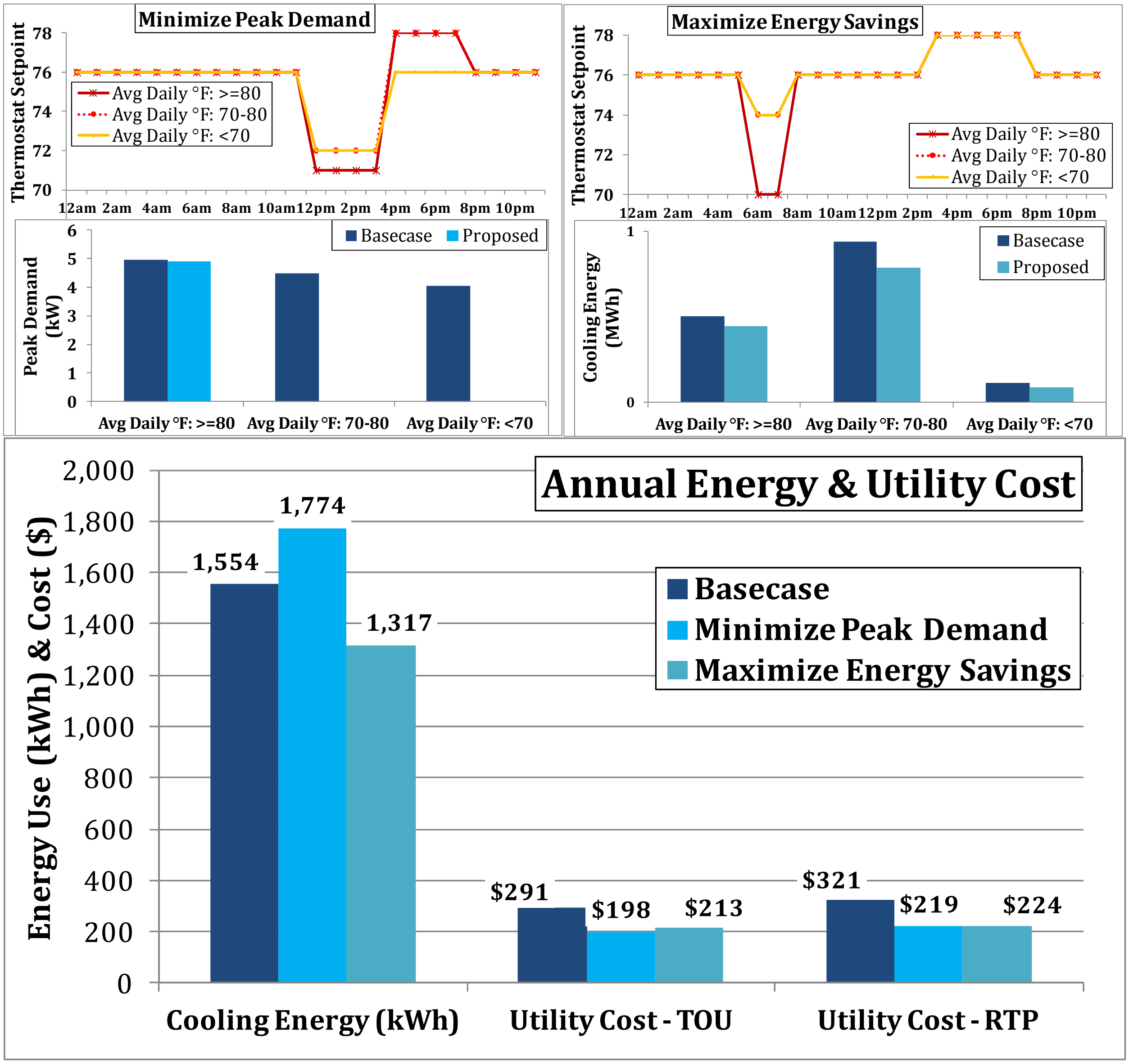

Figure 2. Recommended operating strategies and associated energy and utility cost impacts for a Benchmark home in Sacramento, CA.

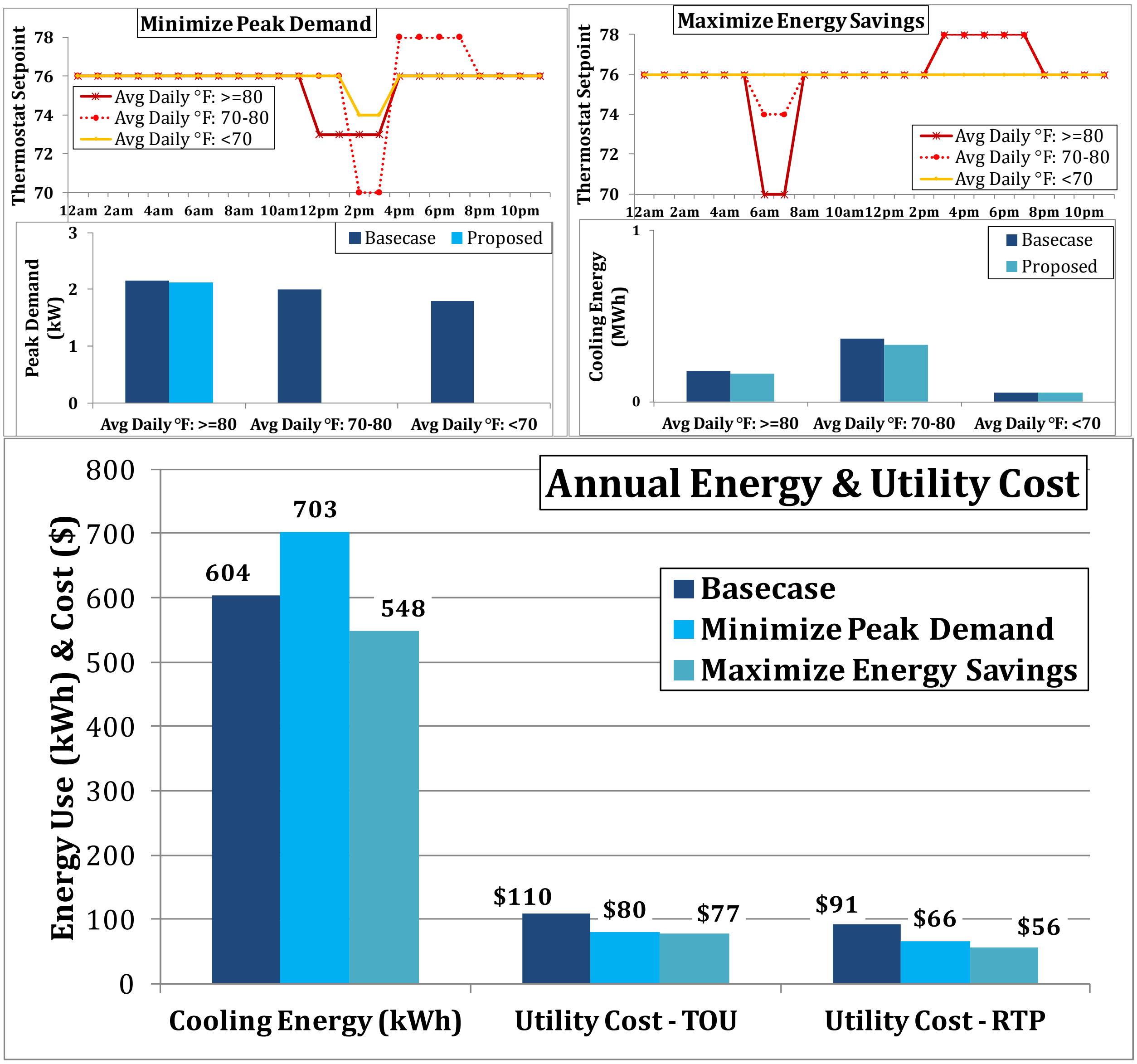

Figure 3. Recommended operating strategies and associated energy and utility cost impacts for a high performance home in Sacramento, CA.

Figure 4 and Figure 5 present results for the Phoenix simulations. Pre-cooling was found to be less effective in this climate compared to Sacramento due to much higher cooling loads and higher daily average temperatures. The TMY3 weather file contains 93 days that reach 100°F. Less than 3% cooling savings were observed for both the Benchmark and the high performance home. However, a 4-5°F setback on all days in the high performance home allowed for shifting of 100% of air conditioner operation to off peak hours. This translated to 22% utility bill savings under the TOU rate assumption.

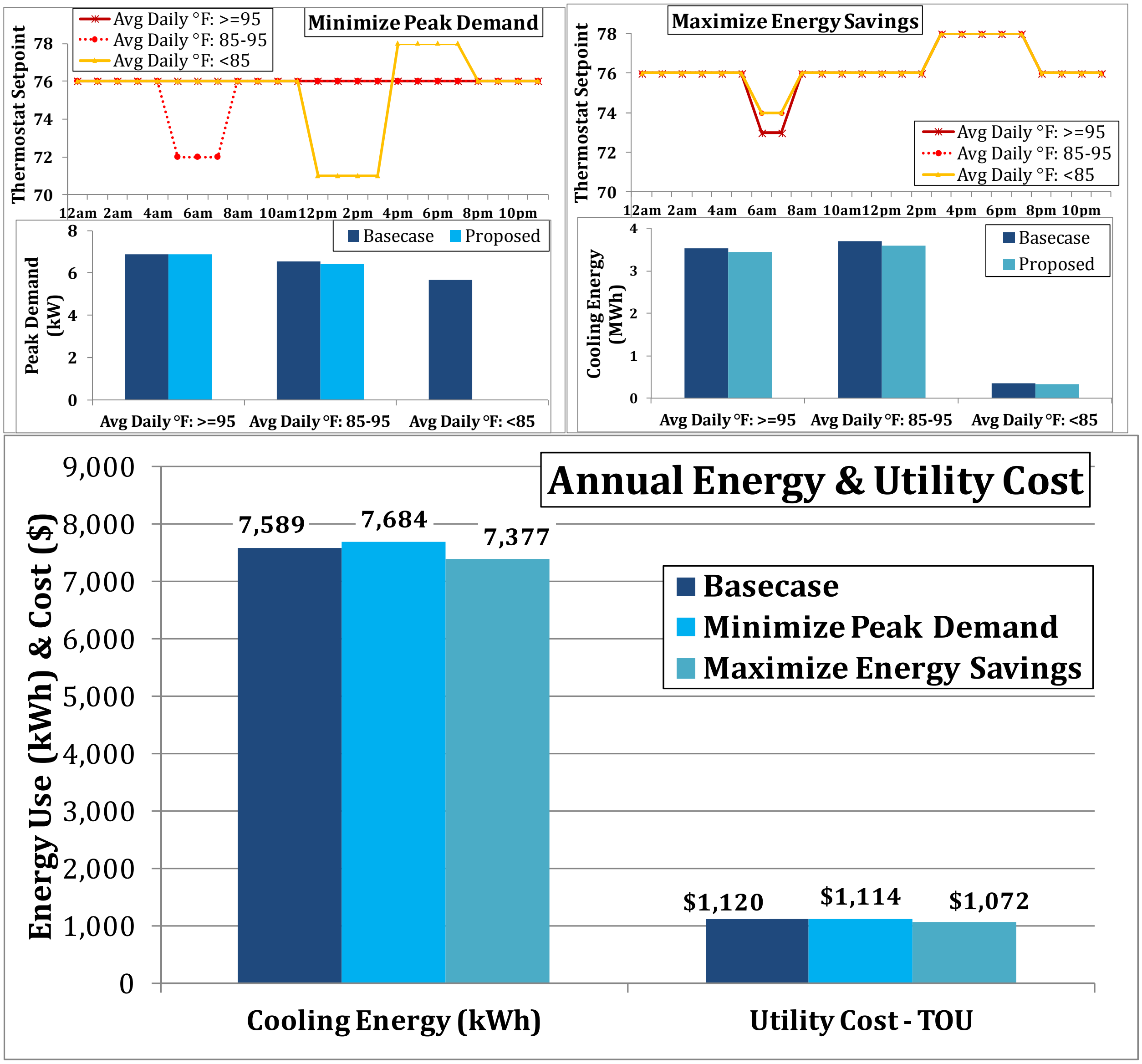

Figure 4. Recommended operating strategies and associated energy and utility cost impacts for a Benchmark home in Phoenix, AZ.

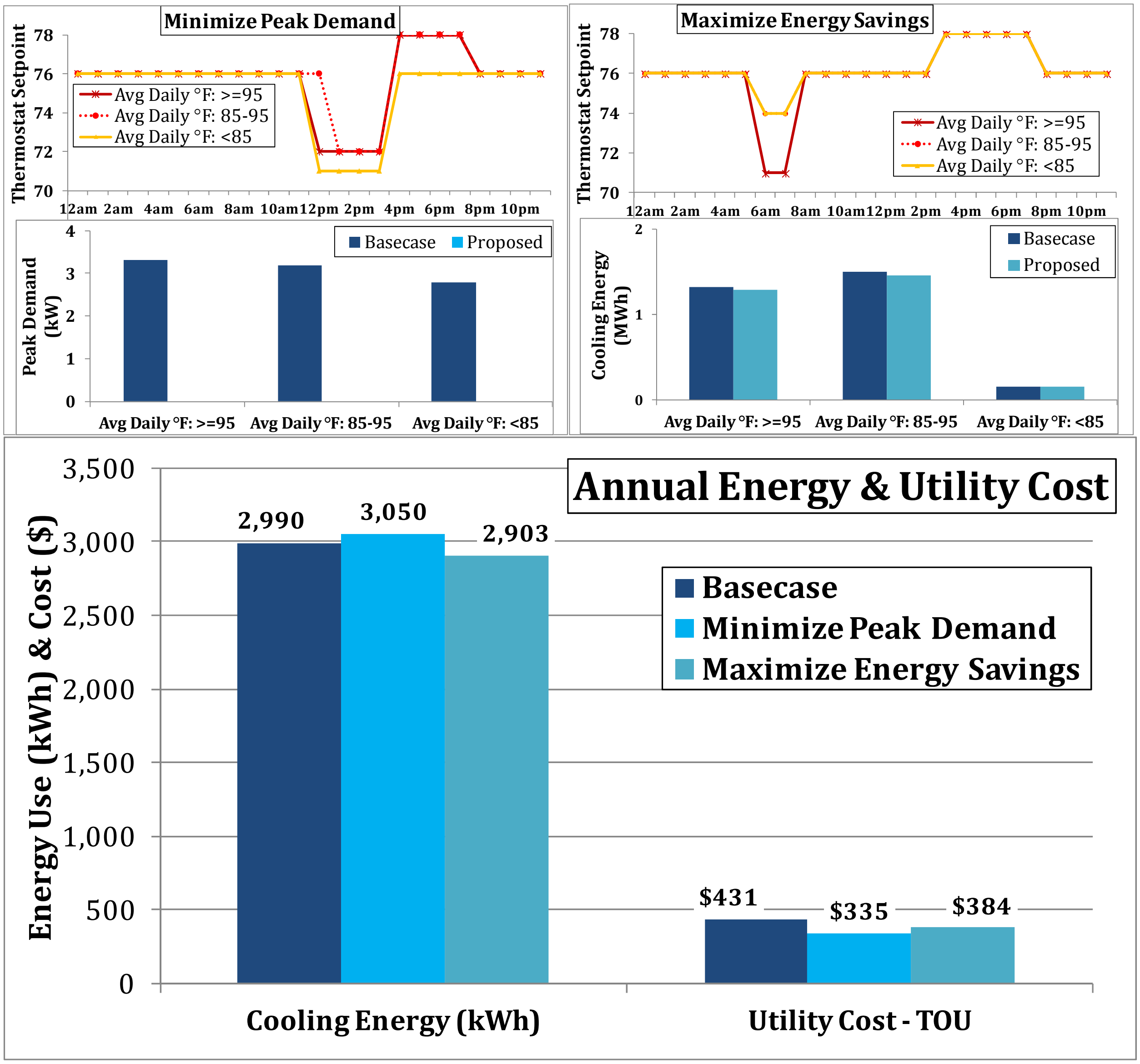

Figure 5. Recommended operating strategies and associated energy and utility cost impacts for a high performance home in Phoenix, AZ.

Field Monitoring of a High Performance Home

During the 2010 and 2011 summers, the authors had the opportunity to test a hypothesis that a house with a radiantly cooled concrete slab floor could effectively be used to both provide comfort and shift peak load in a high performance house located in Tucson, AZ. With support from the DOE sponsored Building America program and with the cooperation of a Tucson home builder, design support was provided to develop a system for a new house and to monitor its performance (German et al. 2012). The four bedroom 1,935 ft^2 one story house featured structural insulated panel (SIP) R-32 walls, a SIP R-41 roof, and an R-10 fully insulated slab with no floor coverings. The cooling system was an air-to-water heat pump delivering chilled water to first a fan coil (for sensible and latent cooling) and then to in-slab radiant tubing.

The installed monitoring system was configured to log data on fifteen minute intervals, although heat flow calculations were completed on 15 second intervals using hydronic flow and immersion temperature sensors. The monitoring scope relevant to this work included capturing indoor and outdoor air temperature and relative humidity, heat pump supply and return water temperature, fan coil supply and return air temperature, and electrical power of the heat pump, fan coil unit, and circulation pumps. Total cooling energy was measured from water flow rates and temperature differences. A one-time measurement of airflow was made which, with fan status, was used to estimate fan coil air-side sensible and latent cooling delivery.

Two temperature schedules were tested to evaluate system performance under different operating conditions during the summer of 2011. These are included in Table 4. The nighttime setback mode is referred to here as "Cool & Coast" (C&C) to reflect the use of the slab to store cooling and maintain indoor temperatures through the hottest periods of the day with no heat pump operation. The fixed setpoint was chosen as an approximate average of the two Cool & Coast settings.

Table 4. Thermostat controls evaluated at the Tuscon test house

Cooling strategy	Setpoint
Fixed setpoint	76ºF Fixed
Cool & Coast (C&C) Pre-cooling	73ºF 12am – 6am 78ºF 6am – 12am

The pre-cooling strategy at the Tucson house used the building's substantial thermal mass in the form of a completely exposed slab floor for storage and close thermal coupling to the indoor space. Figure 6 compares two sets of days with similar outdoor air temperatures (OAT) when both fixed setpoint and the Cool & Coast pre-cooling operating modes were applied. During these test periods the maximum indoor temperature for the fixed setpoint mode was 75.6°F and for the Cool & Coast mode was 78.6°F. Although the Cool & Coast mode resulted in a 3°F higher indoor temperature, the occupants reported to be satisfied with the level of comfort. To achieve lower indoor temperatures would likely require a larger capacity heat pump to meet the extreme demands of this climate.

Figure 7 compares calculated system efficiency (energy efficiency ratio (EER)) and daily energy use as a function of maximum outdoor temperature for the two operating modes. The EER curve for the Cool & Coast mode is much flatter and consistently above that for the heat pump running in constant setpoint mode. Average daily energy use for days with maximum outdoor temperatures greater than 100°F was at least 30% lower for the Cool & Coast mode than for the fixed setpoint mode. Looking at the fifteen minute interval monitoring data, there was a strong correlation between EER and outdoor temperature (R^2 = 0.89) but a very low correlation between EER and entering water temperature (R^2 = 0.06). Even within specific outdoor temperature bins the EER had very low sensitivity to changes in entering water temperature.

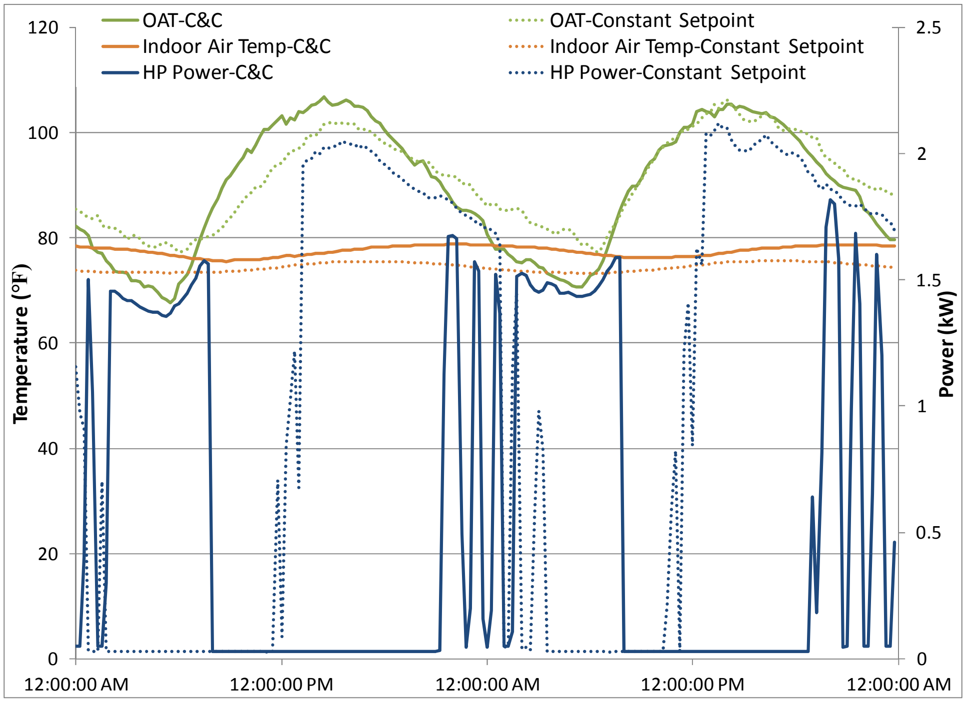

Figure 6. Comparison of indoor temperatures for two two-day periods during which fixed temperature settings and nighttime setback (Cool & Coast (C&C) mode) were applied.

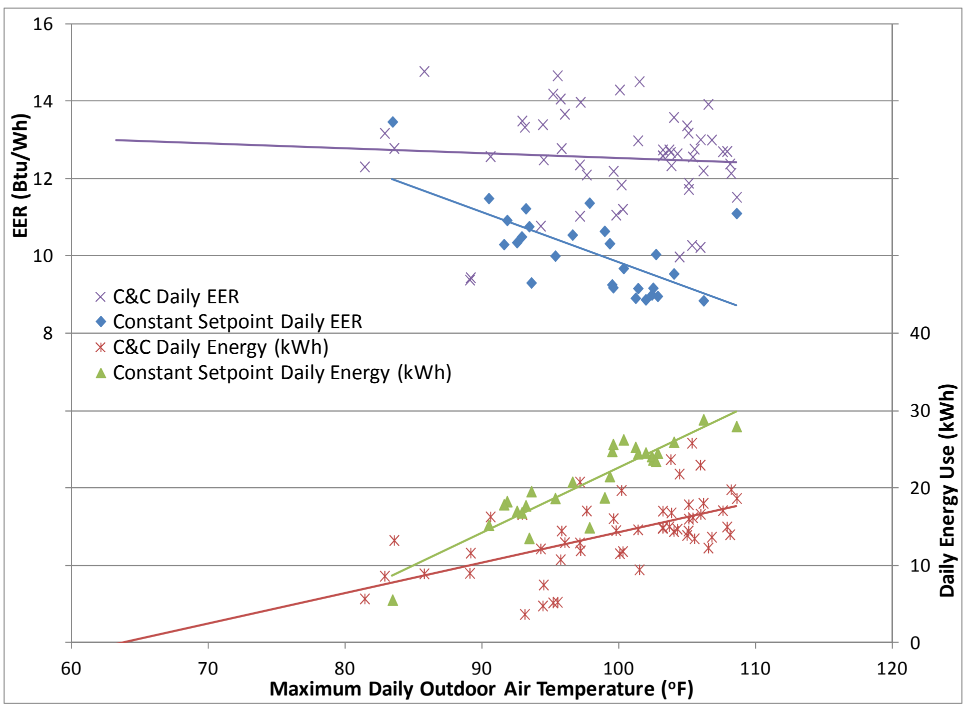

Figure 7. Comparison of measured EER and daily energy use with a fixed thermostat setpoint and a Cool & Coast regime with a 9PM to 8AM temperature setback.

Discussion & Conclusions

Energy modeling with EnergyPlus demonstrated both energy and peak demand savings in the hot-dry climate of Sacramento, CA. Best practice thermostat schedules are dependent on outdoor weather severity (peak vs. mild days) and envelope performance of the home and differ depending if the goal is to maximize energy savings or to minimize peak demand. Effective strategies to target energy savings incorporate a setup of 2°F during the peak hours and result in estimated annual cooling energy savings of 15% for the Benchmark house and 9% for the high performance home. Operation during peak hours can be almost eliminated in a high performance home, with the exception of only a handful of days, resulting in 27% utility bill saving assuming a time-of-use tariff with an electric rate that increases 200% during peak hours; however, the associated energy penalty isn't trivial with a 16% increase in cooling energy consumption.

Greater utility bill savings (close to 50%) were observed under a theoretical real time pricing tariff using morning pre-cooling strategies, which take advantage of cooling system operation during times with fairly inexpensive electricity. This suggests that rates that reflect true utility costs might further value pre-cooling benefits beyond what a TOU rate might reflect. However, the real time pricing tariff in this study was developed based on California's time dependent valuation hourly profiles and further work is necessary to evaluate savings under actual rate structures.

The high performance home in Phoenix, AZ was the only case demonstrating 100% peak demand savings with all cooling operation shifted to non-peak hours. Modeling results estimated less than 3% cooling energy savings from pre-cooling in this climate; however, field monitoring in Tucson, AZ has demonstrated that there can be substantial savings in cases where high levels of thermal mass are available for thermal storage. Monitored cooling energy savings of 30% were observed on peak days with maximum temperatures greater than 100°F, although this also resulted in slightly higher average indoor air temperatures. Recommended future research includes expanding this modeling to incorporate high mass homes that are capable of directly charging thermal mass.

Without a setup to 78°F during the peak hours none of the evaluated strategies resulted in energy savings compared to basecase operation at a constant 76°F setpoint. A similar strategy was utilized in the Tucson monitoring case, the results from which demonstrated satisfactory comfort as reported by the occupants. This type of control may be desirable from the utility standpoint and is already incorporated in some demand response air conditioning programs.

SmartGrid driven innovations and the advent of communicating thermostats allow for additional refinement and sophistication to be added to pre-cooling. Smart controls can conceivably learn how the building responds, what occupants desire in terms of comfort conditions by time of day, and also utilize next day forecasted outdoor temperatures to determine optimal pre-cooling targets. Several advanced thermostat manufacturers and cloud-based systems implementing strategies like this have been demonstrated with major utilities in the Southwestern U.S.in the past few years. With increased interest from utilities and greater sophistication in controls and appliance connectivity, the authors foresee that the future of residential pre-cooling will become more tailored to a specific house, the day's predicted weather, occupant patterns, and the utilities predicted demands.

An additional benefit from cooling during the pre-peak period is integration with photovoltaic (PV) energy production. PV production peaks around mid-day, corresponding with partial-peak or pre-peak periods in many utility areas. Whether the renewable generation is distributed or a central utility scale PV plant, this source can be tied with pre-cooling scheduling to significantly dampen the response required of the utilities' non-renewable power plants. Similar favorable alignment of peak daily wind generation with pre-cooling strategies was observed in the 2007 SMUD over-cooling project.

The authors feel that the research presented here captures a small slice of the broad potential that exists in aligning efficient house design, renewable energy generation, rate design, and residential pre-cooling strategies. Utility demand response programs are becoming more ubiquitous and integrating such programs with pre-cooling affords a valuable opportunity; with the utility providing the signal, pre-cooling can be aligned with off-peak utility rates as well as generation capacity. Electricity stored in stationary or electric vehicle batteries may also become a potential resource as this load type becomes more commonly connected to the grid.

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