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Assessment of peak power demand reduction available via modulation of building ventilation systems

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Disclaimer

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Abstract:
Peak power demand strains electrical grids and increases cost of electricity generation, transmission and distribution infrastructure. Many studies have examined ways of reducing this peak power demand, including modification of room air temperature setpoints or the reduction of lighting levels. However, very few or no studies have examined the peak power reduction resource offered by temporary curtailment of building ventilation systems. For this reason, we conducted a simulation campaign in which we examined the resource offered by temporary ventilation curtailment in commercial buildings of different use types across the United States and in residences in the state of California, with the essential constraint that any changes resulted in air quality acceptable to occupants through additional ventilation to compensate for the curtailment. To do this, we employed previously validated building models implemented in the airflow and contaminant transport tool CONTAM and building thermal and systems modeling tool EnergyPlus, in some cases co-simulated. Results show savings are highly dependent on building type and climate but range from 0-2 W/ft2 and up to 40% of total peak building power demand. Depending on building type, this power shed can be conducted for 1.5-8 hours before acute exposure or odor concerns are expected, assuming a safety factor of 2. This reduction is of the same magnitude as that offered by thermal control strategies such as setpoint increase, or from lighting reduction strategies.

Keywords
ventilation, demand response, peak demand reduction, co-simulation, smart buildings

1. Introduction

Ventilation of buildings serves several purposes. It displaces pollutants of indoor origin associated with both chronic health effects (such as formaldehyde) and acute effects (such as nitrogen dioxide), and it displaces human bioeffluents associated with discomfort, i.e. odors, (ANSI/ASHRAE 2016a and 2016b), and correlated negatively with productivity (Federspiel et al., 2002; Fisk et al., 2002). Building ventilation has profound effects on everything from energy consumption and carbon emissions to electrical grid operation and human health. More than 3% of all U.S. energy consumption is directly attributable to ventilation of commercial buildings and infiltration/ventilation in residences (U.S. EIA 2016).

But a little-discussed effect of building ventilation is its contribution to peak electric power demand. Commercial buildings contribute between 33% and 45% of summer peak demand (Hao et al., 2017; Kiliccote et al., 2006), of which a substantial if not well-known portion is attributable to ventilation. Since ventilation loads are greatest at times when demand is greatest, this effect can be quite profound. Consider one example: If we conservatively assume that in late afternoon during the summer, ventilation is being provided for each person in the New York City metropolitan area at the rates required per person in the current Mechanical Code of New York State, then around 3,000 MW of power is utilized for ventilation alone *in New York City alone* at the hottest times. To put this in perspective, 3,000 MW is around 100 times the grid level storage installed in New York State (U.S. DOE 2017), and around 9% of total New York State summer peak demand (New York ISO 2016). This is both a burden and an opportunity in that shifting this load is relatively easy compared to other strategies like installation of lithium ion battery storage.

Numerous studies have examined the ability of HVAC systems to provide reductions in peak electric power demand. In Table 1 we briefly summarize the results of previous studies of different peak power demand reduction strategies in commercial buildings and we describe these in greater detail in Appendix A. Virtually all strategies involved modification of thermal control of the building (reduction of setpoints at zone, air handler, or chiller) and/or reduction in lighting levels. Some also saved fan power via duct static pressure reduction. The various strategies typically resulted in less than 2 W/ft^2 reduction in power demand (15-30% of building electric power demand).

In Table 2 we briefly summarize the same for residential buildings. The studies included in our literature review of demand response strategies included techniques such as pricing-strategies (i.e. CPP, TOU, RTP, etc.), setpoint changes, or smart control of appliances to shift the demand load. The range of savings was 5%-53%, but the majority of the studies suggested savings in the range 10%-30%.

Table 1. Review of peak power demand reduction strategies analyzed in commercial buildings

Reference	ASHRAE Climate Zone(s)	Building Type	Methods	Field or Simulation	Duration (Window)	Demand Shed
Fernandez et al., 2017	All	Office Building, Retail, School, Large Hotel, Supermarket	Thermal	Simulation	Unknown	0.2%-15.8%
			Lighting	Simulation	Unknown	2.5%
Hao et al., 2017	5B	Office Building	Thermal	Simulation	5min	6.1%-6.3%
Xu et al., 2004	3C	Office Building	Thermal	Simulation + Field	3hr to 9hr (5am-5pm)	1.0-2.3 W/ft^2
Yin et al., 2010	2B, 3B, 3C, 4B, 4C, 5B, 6B	Office Building	Thermal	Field	3hr to 7hr (5am-6pm)	0.2-1.13 W/ft^2
Watson et al., 2006	3B, 3C, 5A, 6A	Office Building, School, Museum, Laboratory, Cafeteria, Data Center, Postal Facility, Library, Retail, Supermarket	Thermal	Field	3hr to 6hr	0.1-1.5 W/ft^2
			Lighting	Field	Unknown	0.2-0.5 W/ft^2
Piette et al., 2007	3C	Office Building, Museum, Data Center, Detention Facility, Laboratory, School, Retail, Supermarket, Bakery	Thermal + Lighting	Field	3hr (3pm-6pm)	0.5-0.72 W/ft^2

Kiliccote & Piette, 2005	3B, 3C, 5A, 6A	Office Building, Bank, Supermarket, Research Facility, Library, Distribution Center	Thermal + Lighting	Field	15min to 6hr	0.1-1.0 W/ft^2
Gu & Raustad, 2001	1A, 4A, 4B, 2B, 6A	Office Building, Retail	Thermal + Lighting	Simulation	15min to 1hr (2pm-5pm)	12.0%-34.0%
Lee & Braun, 2006	5A	Secondary School	Thermal	Field	5hr (1pm-6pm)	1.6-2.7 W/ft^2
Lee & Braun, 2008	3C/2B	Bank (Retail)	Thermal	Simulation	6hr (12pm-6pm)	0.76 W/ft^2
Khanolkar, Reddy, and Addison, 2013	2B	Office Building	Thermal + Lighting	Simulation	1hr to 6hr (12pm-6pm)	25.0%
Li & Xu, 2016	3C	Office Building	Thermal	Simulation + Field	5hr to 7hr (12am-6pm)	1.1-2.3 W/ft^2
Roussac & Huang, 2018	Melbourne & Sydney, Australia	Large Commercial Building	Thermal + Lighting	Field	30min (7am-11pm, 2pm-8pm)	0.3 W/ft^2
Kiliccote, Piette, and Watson, 2006	4A	Office Building	Thermal + Lighting	Simulation	4hr	0.9-1.4 W/ft^2
Parmenter et al., 2008	4B	Office Building	Thermal + Lighting	Simulation	Unknown	15.0%
Stetiu, 1999	2B, 5B, 6B, 5A, 3A, 3C, 4C, 2A, 4A	Office Building	Thermal	Simulation	8hr to 17hr	0.7-1.7 W/ft^2

Table 2. Review of peak power demand reduction strategies analyzed in residential buildings

Reference	ASHRAE Climate Zone(s)	Building Type	Methods	Field or Simulation	Duration (Window)	Demand Shed
Yoon, Bladick, and Novoselac, 2014	2A	Medium/Large Households	Thermal	Simulation	1hr (1pm-7pm)	12.8%-24.7%
Yin et al., 2016	Unknown	Mid- and High-rise Apartments	Thermal	Simulation	4hr to 6hr (12pm-6pm)	40%
Nan, Zhou, and Li, 2018	Suzhou, China	Households	Thermal + Appliance	Simulation	1hr (3pm-6pm)	7.6%-9.0%
Fariqui & Sergici, 2010	France; New South Wales, Australia; Ontario, Canada; 2A; 3B; 3C; 4A; 4B; 4C; 5A; 5B; 6B; 7B	Unknown	Unknown	Field	Unknown	13.0%-20.0%
Newsham & Bowker, 2010	Unknown	Unknown	Unknown	Field	Unknown	30.0%
Bartusch & Alvehag, 2014	Sala, Sweden	Single-family Households, Apartments, and Condominiums	Unknown	Field	(7am-7pm)	10.0%-22.0%
Cole et al., 2014	2A	One- and Two-story Households	Thermal	Simulation	Unknown	5.7%-8.8%
Rhodes, Stephens, and Webber, 2011	2A	Single-family Households	Appliances	Field	Unknown	8%

Croft, Boys, and Covic, 2013	New Zealand	Unknown	Thermal + Appliances	Simulation	Unknown	29.0%
Barbose, Goldman, and Neenan, 2004	Unknown	Unknown	Unknown	Field	1hr (6am-10pm)	12.0%-33.0%
German & Hoeschele, 2014	1A, 2A, 2B, 3B, 4A, 5A, 5B	Two-story Households	Thermal	Field + Simulation	4hr (12pm-4pm)	0-15%

However, to the authors' knowledge, no one has examined the peak power reduction offered through temporary curtailment of ventilation. In practice, virtually all ventilation strategies in buildings are designed to conform to prescriptive per-person and/or per-floor-area ventilation requirements of building codes based on standards such as ASHRAE Standards 62.1 and 62.2 at all times. These required rates can be modulated in response to occupancy signals in order to save energy, which has been shown to be effective by many studies (e.g. Hong and Fisk 2010; Fan et al. 2014; Nielsen and Drivsholm 2010). Recently it has been suggested that rates in residences can also be adjusted in response to real time assessment of infiltration (Ng et al. 2019).

However, ventilation is only one of many contributors to indoor air quality (IAQ). Acknowledgment of this is behind the spirit of the relatively new IAQ Procedure in *ASHRAE Standard 62.1: Ventilation for Acceptable Indoor Air Quality*, which allows ventilation to be provided through a performance-based method. A step forward from the IAQ procedure is the understanding that chronic health effects associated with airborne pollutants are the result of a cumulative effect, and that ventilation can be temporarily modulated or even completely curtailed briefly without sacrificing occupant health or comfort.

This understanding allows for dynamic modulation of ventilation rates- sometimes called "smart" ventilation. This concept has been explored in-depth for residential buildings (Mortensen, Walker, and Sherman, 2011; Sherman, Logue, and Singer, 2011;Less & Walker, 2016; Guyot et al., 2017; Less & Walker, 2017; Guyot, Sherman, and Walker, 2018; Guyot, Walker, and Sherman, 2018; Clark, et al., 2019; Less, et al. 2019). Smart ventilation is based on the theory of "equivalent ventilation" developed by Sherman et al. (2012). Equivalence is quantified through the concept of relative exposure (RE). The RE to a generic pollutant generated at a constant rate in a building, for a given time step, is calculated from the previous relative exposure and the current ventilation rate (Q_i) using Equation 1, unless ventilation is zero, when Equation 2 is used. If the average annual RE provided by a ventilation strategy is equal to one, the strategy is said to be "equivalent" to the baseline (usually code-compliant prescriptive) strategy.

Lastly, in order to ensure acute exposure and odor concerns are avoided, RE should at no time exceed five, as explained in Sherman et al. (2012). This limit of five includes a safety factor of two and was developed after an extensive review of the concentrations at which acute health or comfort effects became a concern for the list of pollutants of interest in indoor environments. Dynamic ventilation control via the RE method is now codified in ASHRAE Standard 62.2-2016, which governs residential ventilation, but is not yet codified in the analogous commercial building ventilation standard. One of the advantages of the relative exposure concept is that it accounts for both occupant-generated pollutants such as bio-effluents, and building-generated pollutants such as formaldehyde via its reference to code-required ventilation rates (which are meant to provide for dilution of both types of pollutants).

$$\boldsymbol{RE_i = \frac{Q_{tot}}{Q_i} + \left(RE_{i-1} - \frac{Q_{tot}}{Q_i}\right) e^{-Q_{tot}\Delta t/V_{space}}} \quad \text{Equation 1}$$

$$\boldsymbol{RE_i = RE_{i-1} + \frac{Q_{tot}\Delta t}{V_{space}}} \quad \text{Equation 2}$$

RE_i = relative exposure for time-step, i
RE_{i-1} = relative exposure for previous time-step, i-1
Q_{tot} = Target ventilation rate from ASHRAE 62.2-2016, m^3/s
Q_i = Ventilation rate from the current time-step, m^3/s
Δt = Simulation time-step, seconds
V_{space} = Volume of the space, m^3

2. Scope and Objectives

In the current study we extend these works through a simulation campaign quantifying the peak demand reduction offered by temporary reduction of ventilation in both residences and commercial buildings. The scope of our analysis of commercial buildings includes nine building types (Small Office, Medium Office, Large Office, Primary School, Secondary School, Retail Store, Supermarket, Small Hotel, and Large Hotel) and climates across the United States. Our analysis of residences is confined to single family homes in the state of California, in which a significant portion of residences have dedicated mechanical ventilation, and where a recent mandate for net-zero residences and large-scale integration of renewable generation is spurring interest in both ventilation and new load shifting strategies.

Our specific objectives are to:

1. Quantify the peak demand reduction and length of complete curtailment possible in each of nine commercial building types across the United States.
2. Quantify the peak demand reduction and length of complete curtailment possible in residences in California.
3. Analyze the consequences of such strategies for indoor air quality and occupant exposure.

3. Methodology

We conducted the two simulation campaigns (single family residences and commercial buildings) in slightly different ways. We first explain the reasoning for this and then go deeper into respective modeling methodologies below.
Single family residences in the United States differ from commercial buildings in that the contribution of natural infiltration to the overall mass balance is more significant in homes. This is because residences tend to be leakier because of their construction methods and their

relatively large surface to volume ratio, and they often include no mechanical ventilation at all. Standards such as ASHRAE Standard 62.2 allow for a “credit” for infiltration which allows for a reduction in mechanical ventilation, in recognition of the significant contribution of infiltration in residences. Conversely, virtually all commercial buildings include dedicated mechanical ventilation, which is assumed by building codes to provide 100% of the air needed to displace pollutants of indoor origin. We make similar assumptions in this work, as described below. Because of the interaction of the exhaust ventilation fan and natural infiltration via changes in internal pressure and neutral pressure plane, in residences it was necessary to calculate airflow across the envelope at every simulation time step (see Less et al. 2019a for a much deeper explanation of this interaction). For this reason, for residences we co-simulated the airflow and contaminant balance software CONTAM with EnergyPlus models of all residences, as was done previously in Clark et al. (2019) and Less et al. (2019a and 2019b). For commercial buildings we assume that infiltration plays an insignificant role in the mass balance, and thus its contribution is neglected. This effectively assumes pressure is controlled to be neutral at all times and infiltration is independent of ventilation rate and minimal. This assumption is conservative in that it doesn’t “take credit” for dilution of indoor pollutants via infiltration in commercial buildings. For this reason, we analyzed commercial buildings using only EnergyPlus and we conservatively assume infiltration does not contribute to mass balances (although it does contribute to energy balances). We describe each of the models in greater detail presently

3.1 Single Family Homes.

We limited the study of single-family homes to the State of California, for a few reasons. First, California recently mandated net-zero home construction, and is the place where such strategies as we propose will have the most immediate effect. Secondly, California has mandated dedicated ventilation in residences in their most recent energy efficiency standard, Title 24-2016: Building Energy Efficiency Standards for Residential and Nonresidential Buildings, and the overwhelming majority of other residences in the United States do not have dedicated ventilation. Lastly, California has quantified the time-varying costs of power generation, transmission, and distribution in their Time-Dependent Valuation (TDV) metric.

For each of the modeled homes we input specifications of the two California Energy Commission single-family prototype units (Nittler & Wilcox, 2006) and ensured properties aligned as well as possible with prescriptive performance requirements (Option B) in the 2016 Title 24 energy code. We modeled two prototype homes: a 1-story 2,100 ft^2 home and a 2-story 2,700 ft^2 home, with forced air space conditioning systems. We created EnergyPlus models of the two prototype homes with BEopt, which automatically generated models and provided default inputs for lighting schedules, internal gains, etc. Conditioning equipment was sized using ACCA Manual J load and parameters describing the homes are given in Appendix A.

While EnergyPlus can model multi-zone air flow and contaminant balances, at the time of model creation it could only account for a single generic contaminant, could not account for contaminant removal within the HVAC system, and was limited in its ability to model the interaction of ventilation systems and infiltration. For these reasons, we created corresponding airflow models in CONTAM (Dols & Polidoro, 2015) in which we modeled homes identical to those modeled in EnergyPlus. Each model had two well-mixed thermal zones, matching the corresponding EnergyPlus model: a single living area; and an attic which was used to capture ceiling airflows and any duct leakage. With these models we were able to capture the combined effect of wind- and buoyancy- driven infiltration, mechanical ventilation fan operation and envelope leakage. This airflow model was the crux of the simulation as it determined both energy and power consequences, and IAQ. This model has previously been field validated in Walker and Wilson (1998) and Walker et al. (1995).

We then co-simulated the corresponding EnergyPlus and CONTAM models in annual simulations using a previously developed protocol (Dols, Emmerich, & Polidoro 2016) which uses a Functional Mockup Unit- (FMI, http://fmistandard.org/) based implementation of CONTAM that is coupled to EnergyPlus via its FMI implementation (Nouidui, et al. 2014). At each timestep, EnergyPlus sent environmental data (wind speed, direction and outdoor temperature), and system operation data (mechanical system flows) to CONTAM. EnergyPlus also calculated the ventilation fan rate. These flow rates were added to the mass balance in CONTAM via “flow paths”. CONTAM then calculated resulting infiltration and inter-zonal airflow, considering these mechanical flows, along with wind-driven and stack effects to determine the resultant mass flow rate. This infiltration is then returned to EnergyPlus to align the two models’ air change rates. After creating our co-simulation models, we verified that the air change rates predicted by CONTAM were correctly transferred to EnergyPlus.

We performed the simulations using:

- Two prototype homes (1-story, 2,100 ft2, 2-story, 2,700 ft2)
- Envelope leakages of 1, 3 and 5 ACH50
- Balanced ventilation systems in 1 ACH50 homes, and simple exhaust fans in the others (3 & 5 ACH50)
- Four California Energy Commission (CEC) climate zones (1 (Arcata), 3 (Oakland), 10 (Riverside), 16 (Blue Canyon)).

3.2 Commercial Buildings.

The simulation of commercial buildings was more straightforward. We employed the standardized U.S. Department of Energy Commercial Reference Buildings models (Deru et al. 2011) that have been extensively validated and used in numerous other works. For further description of these models, the reader is referred to Deru et al. (2011).

We simulated nine building types: Small Office, Medium Office, Large Office, Primary School, Secondary School, Retail Store, Supermarket, Small Hotel, and Large Hotel. These models were simulated in 15 ASHRAE/DOE climate zones covering the entire United States. The representative cities for each climate zone were Miami, FL (1A); Houston, TX (2A); Phoenix, AZ (2B); Dallas, TX (3A); Sacramento, CA (3B); San Francisco, CA (3C); Nashville, TN (4A); Amarillo, TX (4B); Portland, OR (4C); Columbus, OH (5A); Denver, CO (5B); Burlington, VT (6A); Helena, MT (6B); Duluth, MN (7); and Fairbanks, AK (8). Separate building models with envelope and equipment properties appropriate to that climate were used for each climate.

Unlike in the residential modeling, we assumed that infiltration will not contribute to the mass balance in the space, which is a conservative assumption with regards to air quality and exposure. The default EnergyPlus infiltration model DesignFlowRate based on Coblenz and Achenbach (1963) was used for calculating the energy balance in the space in order to quantify peak demand savings, and relative exposure and carbon dioxide mass balance analysis were calculated external to EnergyPlus using the occupancy and required ventilation at peak times. This analysis is much more straightforward than the residential analysis because it does not contain pressure-dependent infiltration terms and thus could be done in a spreadsheet external to EnergyPlus. This also precludes the need to conduct a complex and computationally expensive multi-zone co-simulation of commercial buildings in EnergyPlus and CONTAM. All energy calculations used to quantify demand savings were conducted by EnergyPlus.

3.3 Control Strategies

In residences, we assumed an automatic control strategy operating independent from the owner's input. In order to reduce power at the hottest times of the year, we continuously varied ventilation rate in proportion to outdoor temperature in a control strategy previously analyzed for energy efficiency (Less et al. 2019b). This effectively sets ventilation to zero during peak times while doubling ventilation during milder times and ensures a daily and annual RE of one. A depiction of the strategy is given in Figure 1. In Figure 1, "House Airflow" includes ventilation and infiltration and is almost exclusively ventilation at the hottest times of day (including peak demand times). RE_controller in Figure 1 refers to the relative exposure that the controller calculates, which models the effects of infiltration. Much more detail on this strategy are given in Less et al. 2019b, where it is referred to as VarQ.

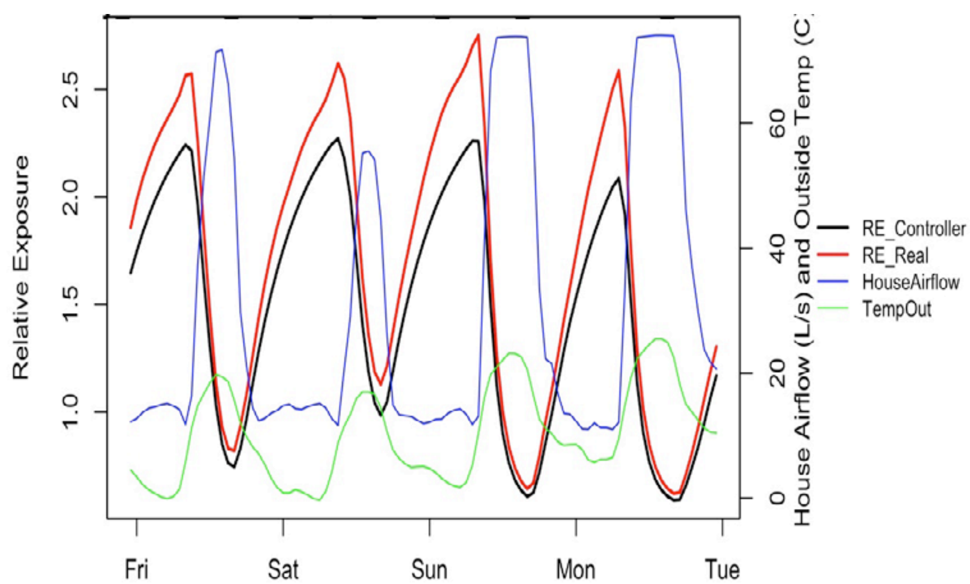

Figure 1. Depiction of the residential temperature-based ventilation control strategy over a typical five-day period in the summer, that essentially curtails ventilation entirely during the hottest periods, usually coinciding with peak demand times.

For each of these time periods, we quantified the power with and without the smart control strategy to calculate the shed available. We also calculated reduction in time dependent valuation (TDV) energy, as is required to demonstrate compliance with the Title 24 building energy code. We used the California Energy Commission (CEC) TDV multipliers for every hour, which are built into the compliance weather files provided by the CEC for use in the CBECC-Res software. At the time the work was conducted the residential TDV calculations were based on the 2012 TDV values. More recent TDV approaches in California have further increased the value of peak energy use and we would expect to see larger TDV savings using more recent TDV values. We combine these with the hourly energy consumption estimates from EnergyPlus for actual energy use to obtain TDV savings.

In commercial buildings, we first calculated the time over which ventilation could be completely curtailed using equivalent ventilation theory as described above. We assumed default occupancy density in accordance with ASHRAE Standard 62.1 to calculate baseline prescriptive ventilation rates. With this established, equivalent ventilation theory provides a constraint of RE not exceeding five to ensure odor and acute exposure concerns are provided for. Given this constraint, we first calculated the amount of time over which we can completely curtail ventilation via Equation 2 using the appropriate baseline ventilation rate per building type.

We then modified ventilation schedules within these models such that ventilation was curtailed completely for the length of the calculated available shed. We then analyzed the resulting effect of reduction in peak power demand in each of the 15 climates and each of nine building types. We also calculated the RE over shed lengths up to four hours using Equations 1 and 2.

For all buildings, we assumed a peak period between 2 and 6pm (in accordance with PG&E rate plans) on the hottest ten days of the year in a particular climate. Weekends and holidays were excluded. Demand reduction events should last at least three hours to capture the critical peak (Kiliccote & Piette, 2005). Therefore, in building types in which the allowable shed was less than three hours, we calculated the reduction in ventilation that was possible for three hours without RE exceeding five during the shed, and without carbon dioxide (CO_2) concentrations exceeding 2,000 ppm. The choice of the 2,000 ppm threshold is somewhat arbitrary, as no study has examined health effects of short-term exposure to concentrations near 2,000 ppm a few days per year. Furthermore, the relationship between steady-state CO_2 concentrations and occupant comfort or health is far from settled. ASHRAE Standard 62.1-prescribed ventilation rates and default occupancy densities result in steady-state CO_2 concentrations of 1,000-1,500 ppm. Seppänen et al. (1999) report concentrations of 350-2,500 ppm are encountered in normal indoor environments. We believe the RE metric is more complete and justified but we include CO_2 concentrations in our results as well for completeness.

4. Results

4.1 Allowable Length of Load Shed Event

Table 3 shows the prescribed ventilation rates in ASHRAE Standard 62.1 or 62.2, as appropriate (normalized as air changes per hour, ACH) and amount of time, Δt, over which ventilation can be completely curtailed in various building types while ensuring. We include both the time length of shed deemed allowable by equivalent ventilation theory ($RE_{max}<5$) and the time over which ventilation can be completely curtailed while holding relative exposure to only 2.5. Additionally, some buildings have multiple space types (e.g. Secondary Schools have classrooms, offices, gymnasiums, and cafeterias) which may produce different Δt values. We chose the zone which has the greatest ventilation requirements per unit floor area, based on required ventilation and occupancy during peak shed hours. This ensures that the Δt used would be sufficient for all zones in the building during peak shed hours.

Table 3. Minimum ventilation rates per ASHRAE Standards 62.1/62.2 and available shed in hours

Space Type	ACH $[h^{-1}]$	Δt [h] RE_{max}=5	Δt [h] RE_{max}=2.5	Zone with Greatest OA Fraction
Large Office	0.57	7.06	2.65	Core Office Space
Medium Office	0.57	7.06	2.65	Core Office Space
Small Office	0.51	7.84	2.94	Core Office Space
Retail Store (Sales)	0.70	5.73	2.15	Core Retail Space
Primary School	2.17	1.84	0.69	Classrooms
Secondary School	2.53	1.58	0.59	Classrooms
Supermarket	0.54	7.41	2.78	Core Supermarket Space
Small Hotel	0.73	5.45	2.05	Guest Rooms
Large Hotel	0.66	6.06	2.27	Guest Rooms
1-Story Residence, 2 Bedrooms	0.31	12.86	4.82	N/A
2-Story Residence, 3 Bedrooms	0.30	13.50	5.06	N/A

As can be seen in Table 3, in building types with large occupancy densities or high ventilation rates, such as schools, ventilation curtailment may not be cost-effective. In space types with lesser occupant densities, such as offices, theory predicts an available shed time of at least five hours, while ensuring relative exposure does not exceed five. If a relative exposure of less than 2.5 (effectively a safety factor of four) is desired, a shed time greater than two hours is predicted for all but the most densely occupied building types.

5.2 Total Power Shed Available in Single Family Homes

The demand reduction in residences in Watts/ft^2 and percentage of total site building energy use, across California climates, is shown in Figure 2. Peak savings varied from approximately 0-30% of total building site power demand during the peak periods. As shown in Figure 2, CEC CZ1 (Arcata) is a poor candidate for such strategies as very little cooling demand exists and in some cases economizer action is negated, resulting in negative savings. The greatest savings occur in in CEC CZ10 (inland southern California), which has the highest cooling demand of any location we assessed.

In general, leakier and taller homes show less potential for savings. This is due to the increased natural infiltration that occurs because of either a greater driving force for infiltration in the case of the 2-story buildings (greater height of building leads to greater stack pressures) or leakier envelope. Greater infiltration rates negate the reduction in ventilation. Thus, these strategies are most appropriate for tight homes with little natural infiltration, such as those being built more often today.

These results contrast somewhat with previously reported analysis of energy savings via smart ventilation control in residences (Clark et al. 2019, Less et al. 2019b). While these previous works showed that little reduction in overall annual electric energy consumption was available in the summer via smart ventilation, the current work shows that the reduction in peak power demand can still be substantial in warmer climates.

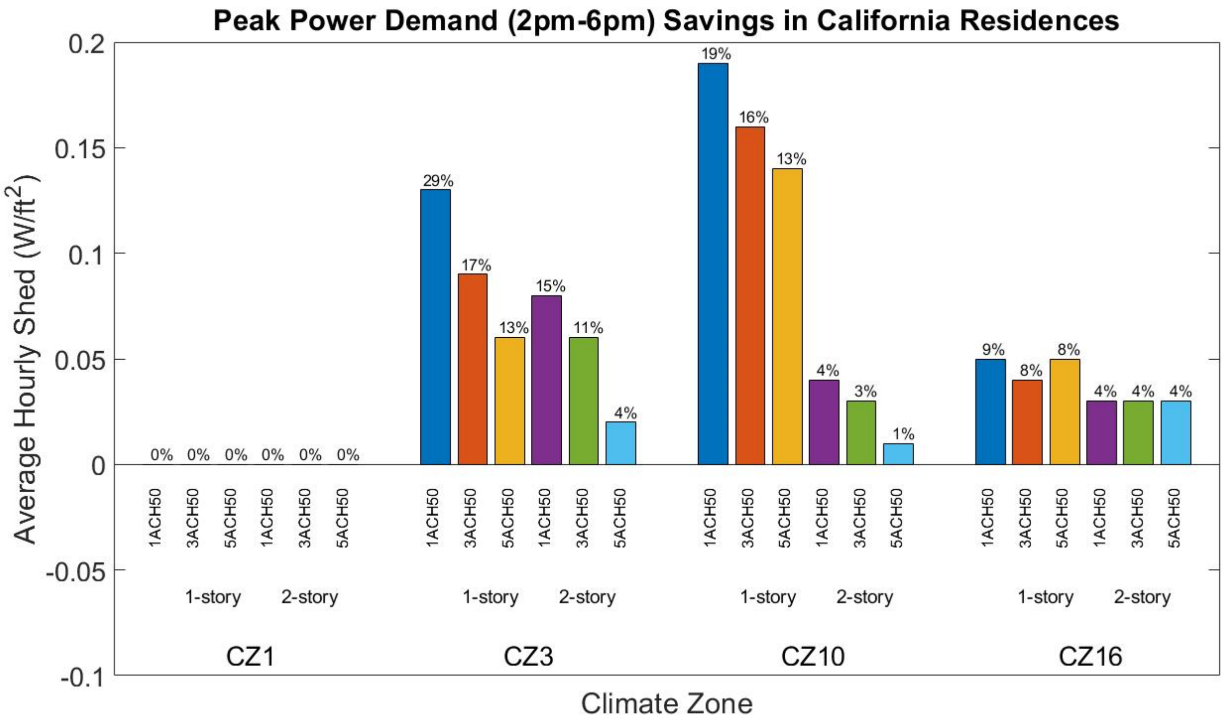

Figure 2. Peak demand (W/ft^2 or %) reduction on the 10 hottest days of the year, 2-6pm, by control type

5.2.1 TDV Savings

TDV savings are shown in Figure 3, with savings ranging from 0-20% and median savings of around 10% of all building TDV energy. Percent TDV ventilation energy savings are fairly consistent across climate zones for all but CEC CZ 1, the coldest climate analyzed. Previous work showed that very little cooling energy savings is achievable through modulation of ventilation in the summer even in warmer climates (Less et al. 2019b) However, these results show that TDV savings can still be appreciable. The TDV multipliers strongly weight electricity consumption during peak cooling periods, and the ventilation curtailment strategy reduced electricity consumption during these periods significantly.

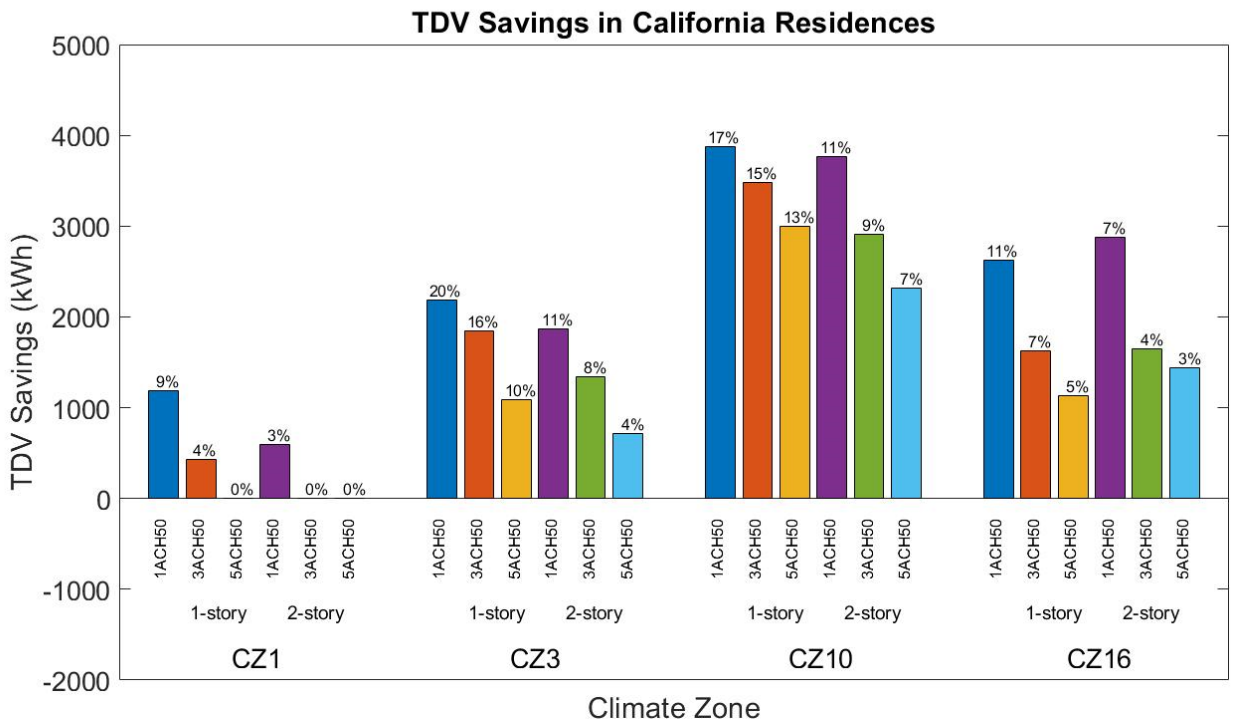

Figure 3. Maximum TDV ventilation energy savings (%), ALL cases

5.3 Total Power Shed Available in Commercial Buildings

Figures 4 and 5 show examples of the power shed available during a ventilation curtailment event from 2pm-6pm, in a Secondary School and Large Office in Miami. These two building types show the limits of performance in the building types analyzed. In the Secondary School only a short shed time period is possible, but a large power shed was realized. Secondary Schools demonstrated 1-hour power demand savings up to 1.93 W/ft^2 and Primary Schools demonstrated 1-hour power demand savings up to 1.07 W/ft^2, both while maintaining a relative exposure less than five. Conversely, in the Large Office less power shed is available, but for a greater period of time.

Figures 4 and 5 also show the resulting relative exposures (black lines) and CO_2 concentrations (purple lines) in the spaces. One can see that in the Office (low occupant density), relative exposure remains under four even after 4 hours of complete curtailment (solid black line). Similarly, assuming a starting steady-state concentration of 1,073 ppm (resulting concentration at ASHRAE 62.1-designated ventilation and occupancy), CO_2 concentrations reach a peak CO_2 concentration of 2,487 ppm during a 3-hour ventilation curtailment period (solid purple line). This peak number can be reduced by implementing a "flush" period in which the office is over-ventilated in anticipation of a demand response event. At the other extreme, the high-density classrooms are poor candidates for such curtailment as CO_2 concentrations and relative exposure would still exceed acceptable values for sheds longer than an hour.

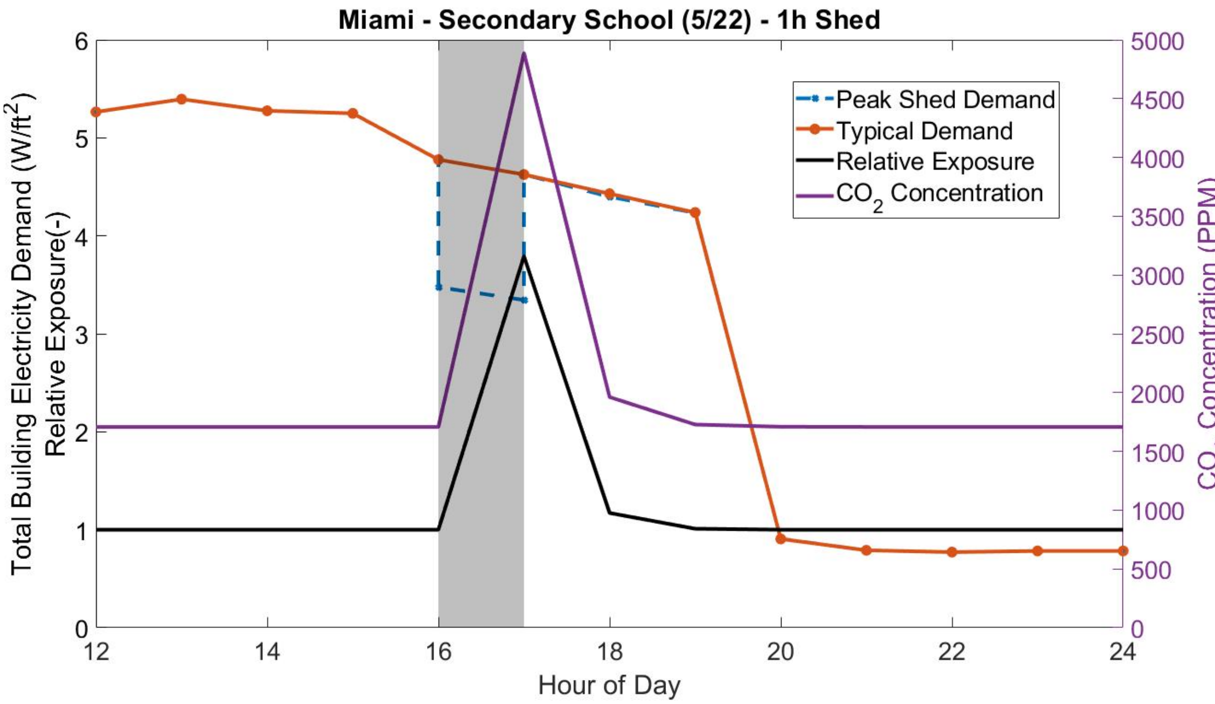

Figure 4. Site power demand, relative exposure, and CO_2 concentrations during a peak power shed event in a Secondary School in Miami, FL on TMY3 March 22nd

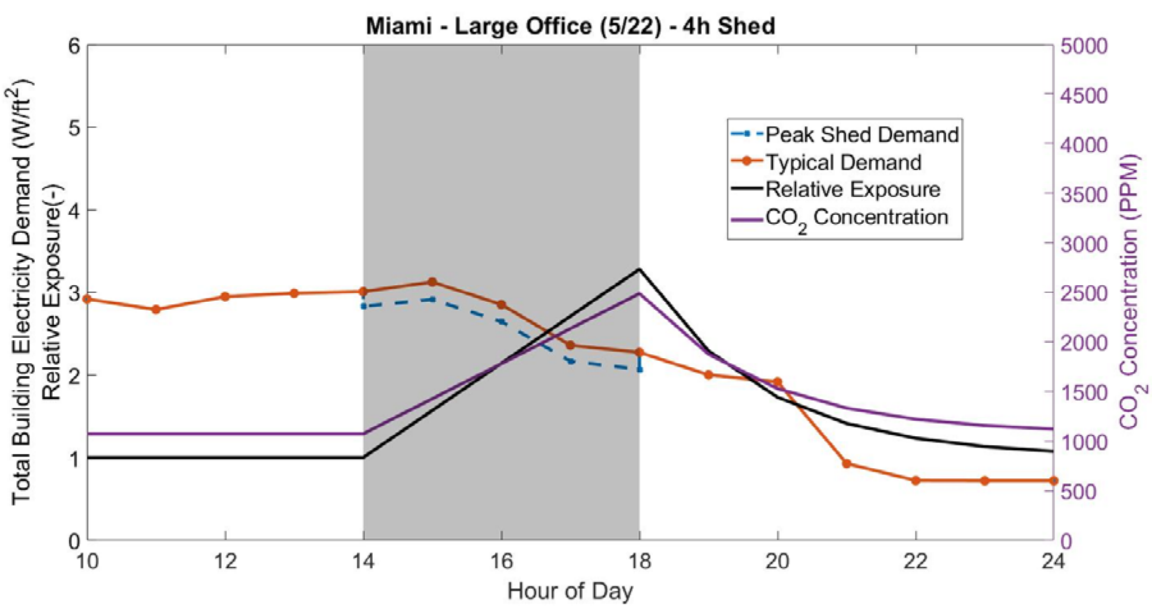

Figure 5. Site power demand, relative exposure, and CO_2 concentrations during a peak power shed event in a Large Office in Miami, FL on TMY3 March 22nd

We show the power shed available in these two building types (Large Office and Secondary School) across the climates in the United States in Figures 6 and 7. As expected, warm and/or humid climate zones (1A, 2A, 2B, and 3A) showed the greatest potential for peak power demand shed. In warmer climates, 5-12% of the entire building power demand can be shed safely in Large Offices by curtailing ventilation, or 0.15-0.33 W/ft^2. This amount of shed is comparable to that found in previous studies from increase in temperature setpoints, and can be achieved in a way that is likely imperceptible to occupants, assuming equivalent ventilation theory is correct. Not surprisingly, colder climate zones 3C (San Francisco, CA) and 8 (Fairbanks, AK) showed much less potential for demand shed, sometimes producing negligible changes to peak power demand.

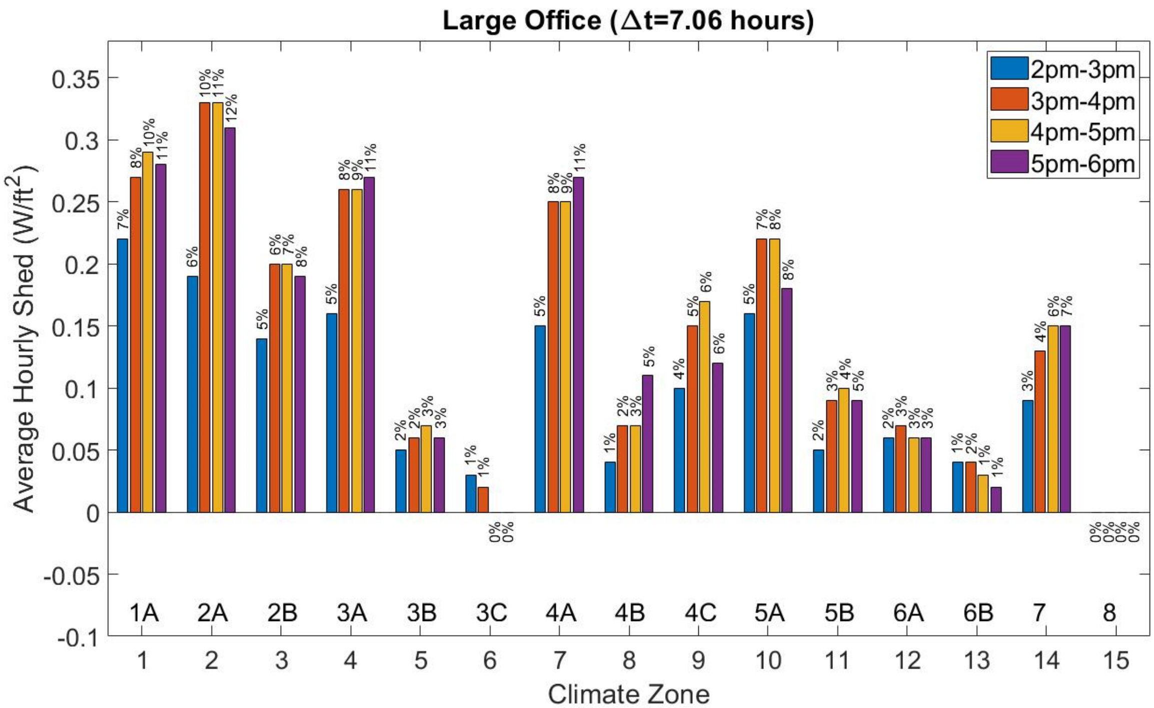

Figure 6. Site power demand shed during 4-hour ventilation curtailment during peak hours (2pm-6pm) for 10 of the hottest weekdays of the TMY3 for Large Offices in 15 different climate zones

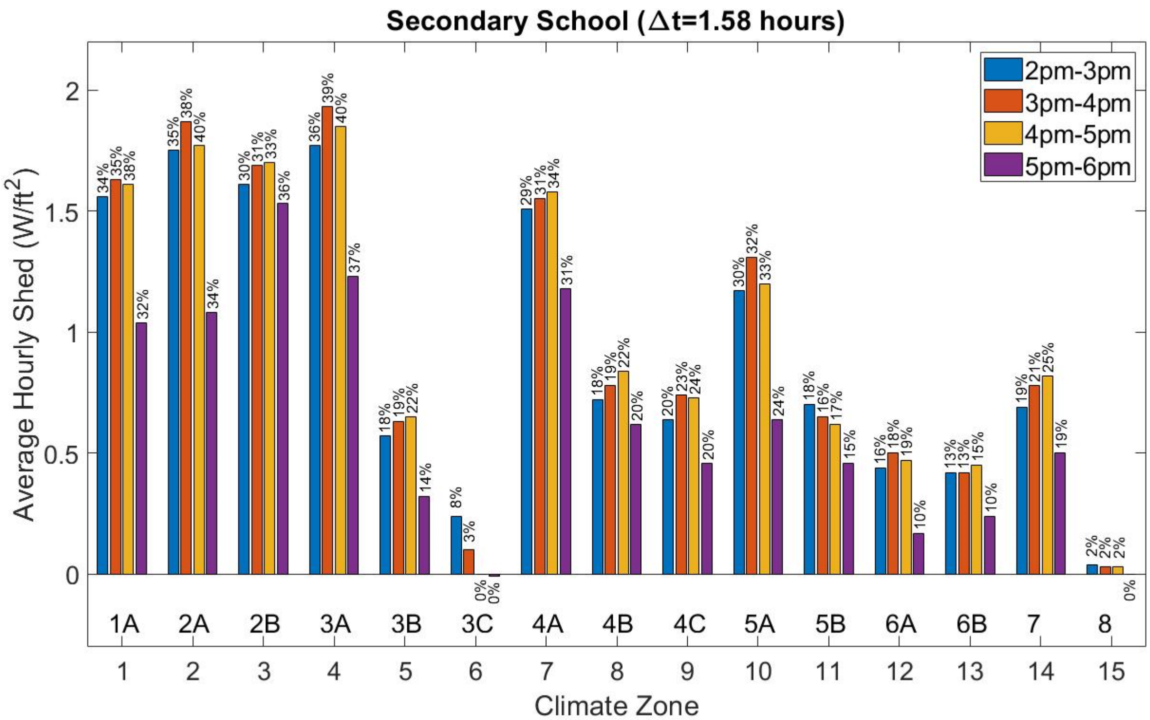

Figure 7. Site power demand shed during a 4-hour ventilation curtailment during peak hours (2pm-6pm) for 10 of the hottest weekdays of the TMY3 for Secondary Schools in 15 different climate zones

In Appendix B, we show figures similar to Figure 6 and 7 for the other building types. In general, these results fall in between the two extreme cases shown in Figures 4-7. Building types with large occupancy density showed large shed potential but for only short periods of time. For example, stand-alone retail stores showed the next-greatest potential for peak power demand reduction, showing power demand savings ranging up to 0.78 W/ft^2 for. Buildings with less occupant density nonetheless show shed potential of the order of magnitude of that demonstrated previously via thermal control strategies, and over the entire amount of time expected for a typical peak shedding event. The other building types all provided similar potentials for peak power demand reduction, with maximum power demand savings of 0.51, 0.78, and 0.44 W/ft^2 for Offices, Supermarkets, and Hotels, respectively.

5.2.1 Extending the Shed in Secondary and Primary Schools

In general, we expect peak demand reduction events will need to be at least three hours long to be implemented. As previously shown, Secondary and Primary Schools have allowable shed times of 1.58 and 1.84 hours, respectively, with complete ventilation curtailment. In order to extend the length of the shed period in these building types, we devised a new strategy, described previously, in which we curtail ventilation somewhat but not completely and maintain relative exposure below five and CO_2 concentrations below 2,000 ppm. With this convention, the Secondary School required a ventilation rate of 81% of the code-required prescriptive rate, while the Primary School required a ventilation rate of 50% of the code rate. As shown in Figures 8 and 9, reducing ventilation in this way rather than curtailing completely results in 3-hour peak power demand reduction for a Secondary School in Miami, FL of approximately 0.26 W/ft^2, compared to a 1-hour shed of 1.59 W/ft^2. This new value is similar to that calculated for other building types.

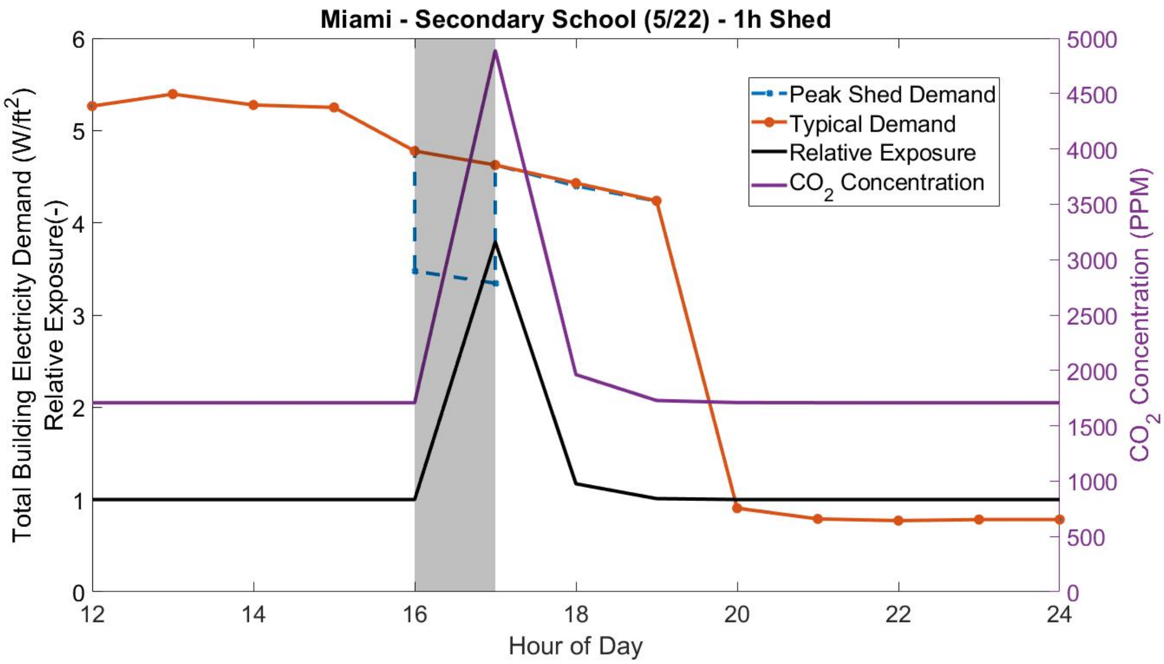

Figure 8. Complete curtailment: Power demand, relative exposure, and CO_2 concentrations during a 1-hour ventilation complete curtailment of ventilation for a Secondary School in Miami, FL during typical shed event.

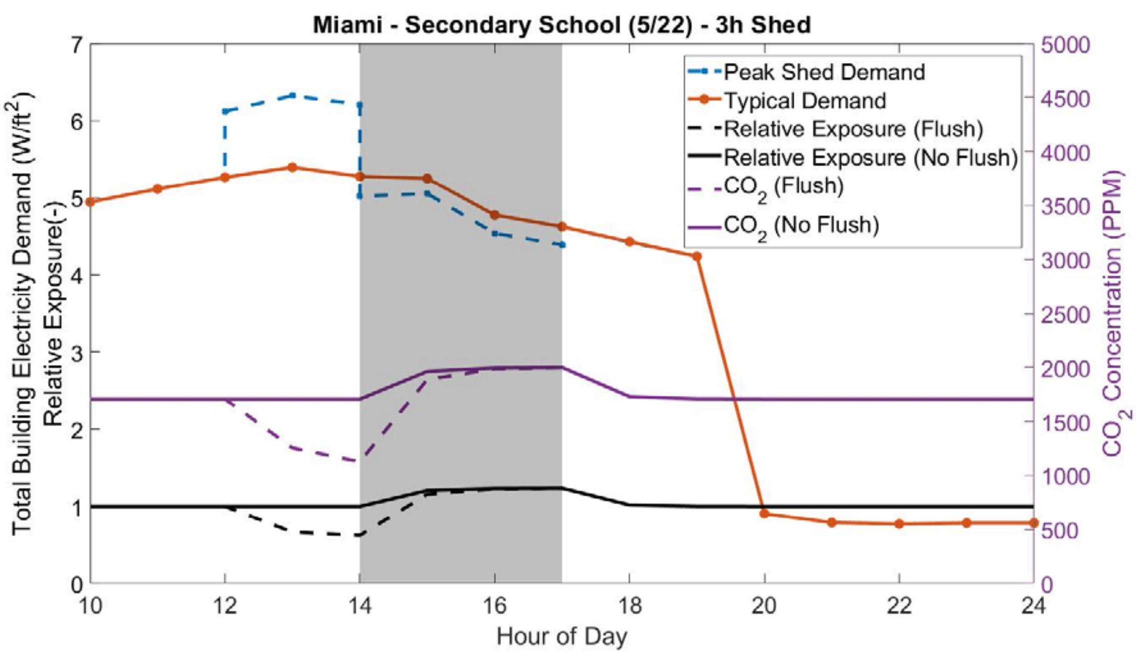

Figure 9. Power demand, relative exposure, and CO_2 concentrations during a 3-hour partial ventilation curtailment (ventilation rate= 81% of standard-compliant rate) for a Secondary School in Miami, FL during typical shed event

Figures 10 and 11 show the power shed available in these two building types across all climate zones. With the reduced-ventilation strategy, power shed is similar to that calculated for complete curtailment in other building types, and also comparable to previously studied thermal control strategies.

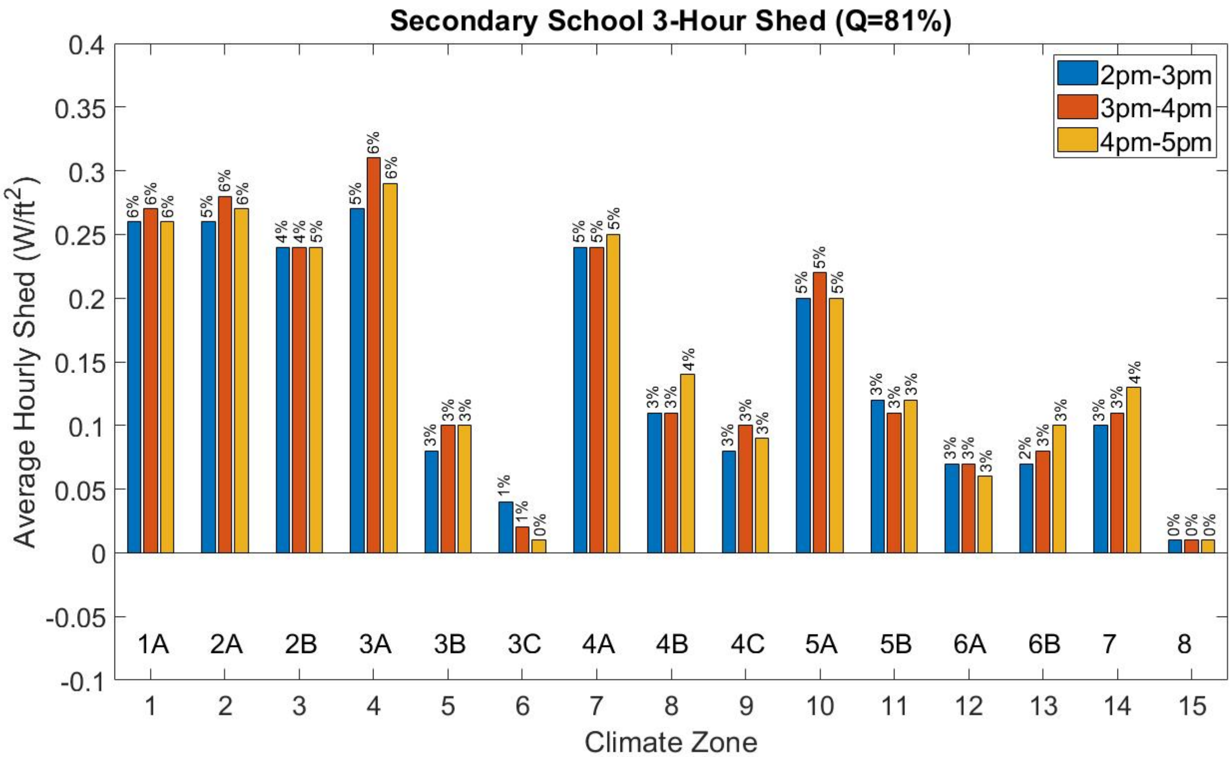

Figure 10. Power demand, relative exposure, and CO_2 concentrations during a three-hour (2pm-5pm) ventilation reduction (Q=81%) event during peak hours for 10 of the hottest weekdays of the TMY3 year for Secondary Schools in 15 different U.S. climate zones

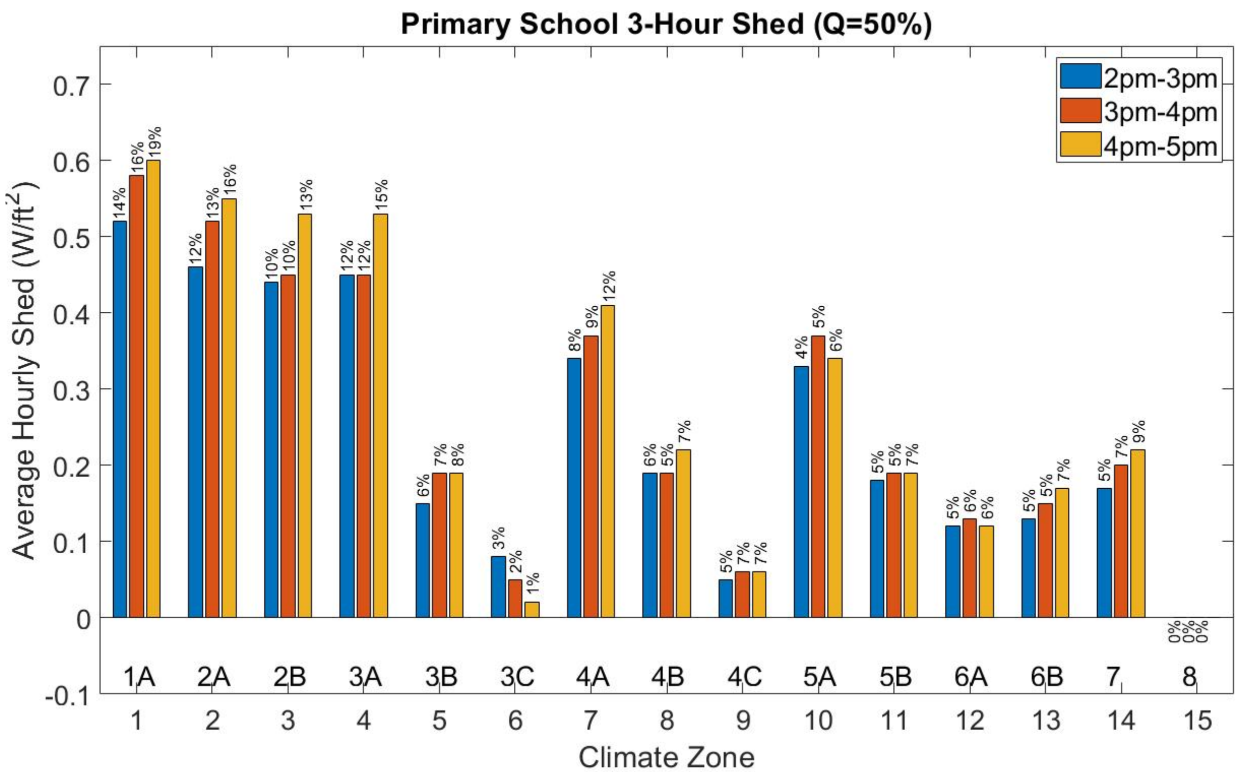

Figure 11. Power demand, relative exposure, and CO_2 concentrations during a three-hour (2pm-5pm) ventilation reduction (Q=81%) event during peak hours for 10 of the hottest weekdays of the TMY3 year for Primary Schools in 15 different U.S. climate zones

6. Discussion and Conclusions

This study quantified how ventilation reduction or curtailment can contribute to peak power demand reduction in buildings, and how these strategies compare to existing demand response strategies in residential (i.e. smart appliances, temperature setpoint changes, etc.) and commercial (lighting, thermal, etc.) buildings.

The results of this study's simulation of 1- and 2- story residential buildings in California climates showed:

- Ventilation can be curtailed completely in typical energy efficient homes for approximately five hours while ensuring a safety factor of four is maintained for acute health and comfort concerns.
- Residences in California offer the potential for up to 0.2 W/ft^2 or up to 30% of total building power demand during peak periods.
- They also offer a median TDV savings of around 10% of all building TDV energy in California, with greatest individual home savings up to 20%. Although previous work (Less et al. 2019b) showed little cooling energy reduction was available with smart ventilation control in the summer in California, this suggests that nonetheless substantial TDV savings can be achieved because of the high cost of electricity at peak times in the summer.

- Colder climates are not likely good candidates for targeting peak reduction via ventilation, as little summer peak cooling power demand exists. The warmest climates were the climates with the greatest savings realized.

The results of this study's simulation of nine commercial buildings in 15 ASHRAE climate zones showed:

- Ventilation can be completely curtailed in many building types over a 3-hour period, and in buildings with greater occupancy density and thus required ventilation rates, a reduction in ventilation can offer peak power demand savings comparable to complete curtailment in less dense building types.
- Humid climate zones (A) had greater peak power demand reductions compared to most dry (B) or marine climates (C), with sheds of approximately 10% of all building power demand in many building types in humid climates.
- ASHRAE Climate Zones 3C and 8 (colder summers) are not good candidates for peak demand reduction via ventilation curtailment due to negligible changes to peak power demand and even instances of increases in power demand.
- Building types with greater occupancy density such as Secondary and Primary Schools have the greatest potential for peak power demand reductions of the building types analyzed, approaching 2 W/ft^2 in some climates, but had the smallest allowable complete ventilation curtailment times, less than two hours.
- A literature review of previous commercial demand response strategies showed a range of 0-2 W/ft^2 and/or up to 40% of total peak building power demand, with sheds near 10% being most common. Ventilation strategies have not been heavily examined as potential peak power demand reduction or load shifting strategy, but these findings suggest that under certain circumstances ventilation strategies can produce comparable savings to existing peak power demand reduction strategies while preserving occupant comfort and health.

This study relied on equivalent ventilation theory for its assessment of the indoor air quality impacts of ventilation curtailment or reduction. It does not capture changes in indoor concentrations of predominantly outdoor-generated pollutants when ventilation is modified and effectively assumes that outdoor air is "perfect" if minimum filtration requirements are met and intakes are sited properly, much like both ASHRAE Standards 62.1 and 62.2. There is also no guarantee of human health and well-being if relative exposure limits are met, as relative exposure references code-required ventilation rates and these rates are not intended to ensure human health and well-being, but rather acceptability of air. Further experimental research in which occupant comfort is quantified through surveys and real-time sensing of pollutants is needed to prove ventilation can be used as a successful peak power demand reduction or load shifting strategy while ensuring occupant health and comfort. This modeling study also may not have captured second-order effects that may affect assessments of power reduction potential, and thus results must be validated in real buildings before such strategies are widely implemented. Lastly, the type of ventilation curtailment strategies analyzed in this work are not yet allowable by ASHRAE Standard 62.1-2019, although they are allowable in the analogous residential standard. Nonetheless this work suggests a path to substantial savings.

References

1. ANSI/ASHRAE (2016) ANSI/ASHRAE Standard 62.1-2016 Ventilation for Acceptable Indoor Air Quality. ASHRAE.
2. ANSI/ASHRAE (2016) ANSI/ASHRAE Standard 62.2-2016 Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings. ASHRAE.
3. Barbose, G., Goldman, C., and Neenan, B. (2004). A Survey of Utility Experience with Real Time Pricing. LBNL-54238.
4. Bartusch, C. & Alvehag, K. (2014). Further exploring the potential of residential demand response programs in electricity distribution. Applied Energy, (125):39-59.
5. Clark, J., Less, B., Dutton, S., Walker, I., and Sherman, M. (2019). Efficacy of occupancy-based smart ventilation control in residences in California and the United States. Building and Environment (156):253-267.
6. Coblenz, C. W. and Achenbach, P. R. 1963. Field Measurement of Ten Electrically-Heated Houses. ASHRAE Transactions pp 358-365.
7. Cole, W., Rhodes, J., Gorman, W., Perez, K., Webber, M., and Edgar, T. (2014). Community-scale residential air conditioning control for effective grid management. Applied Energy (130):428-436.
8. Croft, A., Boys, J., and Covic, G. (2013). Net Energy Stored Control for Residential Demand-side management. 39th Annual Conference of the IEEE Industrial Electronics Society, Vienna, Austria, November.
9. Demand Controlled Ventilation in Residences. International Journal of Ventilation, 10(1):49-60.
10. Deru, et al. (2011). U.S. Department of Energy Commercial Reference Building Models of the National Building Stock. NREL/TP-5500-46861. NREL: Golden, CO.
11. Fan, Y., K.Kameishi, S. Onishi, K. Ito. (2014). Field-based study on the energy-saving effects of CO2 demand controlled ventilation in an office with application of Energy recovery ventilators. Energy and Buildings, Volume 68, Part A, pp. 412-422
12. Faruqui, A., & Sergici, S. (2010). Household response to dynamic pricing of electricity: a survey of 15 experiments. Journal of Regulatory Economics, 38(2):193-225.
13. Federspiel, C.C., Lie, G., Lahiff, M., Faulkner, D., DiBartolomeo, D.L., Fisk, W.J., Prince, P.N., and Sullivan, D.P. (2002). Worker Performance and Ventilation: Analyses of Individual Data for Call-Center Workers. Proceedings, Indoor Air 2002, Monterey, CA, June. LBNL-50124.
14. Fernandez, N., Xie, Y., Katipamula, S., Zhao, M., Wang, W., and Corbin, C. Impacts of Commercial Building Controls on Energy Savings and Peak Load Reduction. PNNL/DE-AC05-76RL01830.
15. Fisk, W.J., P. Price, D. Faulkner, D. Sullivan, D. Dibartolomeo, C. Federspiel, G. Liu, and M. Lahiff. (2002). Productivity and ventilation rate: Analyses of time-series data for a group of call center workers. Proceedings of Indoor Air 2002, Monterey, CA, June.
16. German, A., & Hoeschele, M. (2014). Residential Mechanical Precooling. U.S. Department of Energy, Energy Efficiency & Renewable Energy.
17. Gu, L., & Raustad, R. (2011). Short-term Curtailment of HVAC Loads in Buildings. ASHRAE Research Project 1390-RP UCF/FSEC 20128171.

18. Guyot, G., I. Walker, M. Sherman, and J. Clark. (2017). Residential smart ventilation: A review. LBNL-201056.
19. Guyot, G., Sherman, M.H. and Walker, I.S. (2018). Smart ventilation energy and indoor air quality performance in residential buildings: a review. Energy and Buildings, 165(15):416-430.
20. Guyot, G., Walker, I. S., & Sherman, M. H. (2019). Performance based approaches in standards and regulations for smart ventilation in residential buildings: a summary review. International Journal of Ventilation, 18(2):96-112.
21. Hao, H., Corbin, C., Kalasi, K., and Pratt, R. (2017). Transactive Control of Commercial Buildings for Demand Response. IEEE Transactions on Power Systems, 32(1):774-783.
22. Hong, T. and W. Fisk. (2010). Assessment of Energy Savings Potential from the Use of Demand Controlled Ventilation in General Office Spaces in California. Building Simulation 3 (2)
23. Khanolkar, A., Reddy, A., & Addison, M. (2013). Short Term Notification Demand Response Measures in Office Buildings in a Hot and Dry Climate. 2013 Annual ASHRAE Conference, Denver, CO.
24. Kiliccote & Piette. (2005). Advanced Control Technologies and Strategies Linking Demand Response and Energy Efficiency. 5th International Conference on Enhanced Building Operations, Pittsburgh, PA, September. LBNL-58179
25. Kiliccote & Piette. (2006). Advanced controls and Communications for Demand Response and Energy Efficiency in Commercial Buildings. Second Carnegie Mellon Conference in Electric Power Systems: Monitoring, Sensing, Software and Its Valuation for the Changing Electric Power Industry, Pittsburgh, PA, January. LBNL-59337.
26. Kiliccote, S., Pietter, M.A., and Watson, D.S. (2006). Dynamic Controls for Energy Efficiency and Demand Response: Framework concepts and a New Construction Study Case in New York Proceedings, 2006 ACEEE Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA, August. LBNL-60615
27. Koomey, J., & Brown, R. E. (2002). The role of building technologies in reducing and controlling peak electricity demand. LBL-49947.
28. Lee K., & Braun, J.E. (2006). An Experimental Evaluation of Demand-Limiting Using Building Thermal Mass in a Small Commercial Building. ASHRAE Transactions, (112):559-571.
29. Lee, K. & Braun, J.E. (2008). A Data-Driven Method for Determining Zone Temperature Trajectories that Minimize Peak Electrical Demand. ASHRAE Transactions, 114(2).
30. Less, B. & Walker, I.S. (2016). Smart Ventilation Control of Indoor Humidity in High Performance Homes in Humid U.S. Climates. LBNL-1006980.
31. Less, B., & Walker, I.S. (2017). Smart Ventilation Controls for Occupancy and Auxiliary Fan Use Across U.S. Climates. LBNL-2001118.
32. Less, B., S. Dutton, X. Li, J. Clark, I. Walker and M. Sherman. (2019a). Smart Ventilation for Advanced California Homes-Single Zone Technology Task. LBNL- 2001206.
33. Less, B., Dutton, S., Walker, I., M. Sherman and J. Clark (2019b). Energy savings with outdoor temperature-based smart ventilation control strategies in advanced California homes. Energy and Buildings (194) 317-327. https://doi.org/10.1016/j.enbuild.2019.04.028

34. Li, W., & Xu, P. (2016). A fast method to predict demand response peak load reductions of commercial buildings. Science and Technology for the Built Environment, 22(6):633-642.
35. Logue, J.M., McKone, T.E., Sherman, M.H., and Singer, B.C. (2011). Hazard assessment of chemical air contaminants measured in residences. Indoor Air, 21(2):92-109.
36. Lu, X., Lu, T., and Vijanen, M. (2011). Estimation of Space Air Change Rates and CO2 Generation Rates for Mechanically-Ventilated Buildings. Advances in Computer Science and Engineering, Chapter 12, 238-260.
37. Mortensen, D. K., Walker, I. S., & Sherman, M. H. (2011). Optimization of Occupancy Based Demand Controlled Ventilation in Residences. International Journal of Ventilation, 10(1):49-60.
38. Nan, S., Zhou, M., & Li, G. (2018). Optimal residential community demand response scheduling in smart grid. Applied Energy, (210):1280-1289.
39. New York ISO (2016) Power Trends 2016
40. Newsham, G., & Bowker, B. (2010). The effect of utility time-varying pricing and load control strategies on residential summer peak electricity use: a review. Energy Policy, 38(7):3289-3296.
41. Nielsen, T. and C. Drivsholm. 2010. Energy efficient demand controlled ventilation in single family houses. Energy and Buildings 42 (11) pp.1995-1998
42. Ng, L., S. Zimmerman, J.Good, B.Tool, S. J. Emmerich, A.K. Persily. (2019). Estimating real-time infiltration for use in residential ventilation control. Technical Note (NIST TN) – 2046. NIST: Gaithersbrug, MD.
43. Parmenter, K.E., Hurtado, P., Wikler, G., and Gellings, C.W. (2008). Dynamic Energy Management. 2008 ACEEE Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA, August.
44. Permentier, K., Vercammen, S., Soetaert, S., Schellemans, C. (2017). Carbon dioxide poisoning: a literature review. International Journal of Emergency Medicine (10)14.
45. Persily, A. & de Jonge, L. (2017). Carbon dioxide generation rates for building occupants. Indoor Air, 27(5):868-879.
46. Piettet, M.A., Watson, D.S., Motegi, N., and Kiliccote, S. (2007). Automated Critical Peak Pricing Tests: 2006 Pilot Program Description and Results. LBNL-62218.
47. Rhodes, J.D., Stephens, B., & Webber, M.E. (2011). Using energy audits to investigate the impacts of common air-conditioning design and installation issues on peak power demand and energy consumption in Austin, Texas. Energy and Buildings, 43(11):3271-3278.
48. Roussac, C.A., & Huang, H. (2018). Forewarned is Forearmed: Reducing Peak Demand in Commercial Buildings with Behavior Science. 2018 ACEEE Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA, August.
49. Seppanen, O., W.J. Fisk and M.J. Mendell. (1999). Association of Ventilation Rates and CO2 concentrations with health and other responses in commercial and institutional buildings. Indoor Air, 9(4):226–252.
50. Sherman, M. H., Logue, J. M., & Singer, B. C. (2011). Infiltration effects on residential pollutant concentrations for continuous and intermittent mechanical ventilation approaches. HVAC&R Research, 17(2):159–173.

51. Sherman, M.H., Walker, I.S. & Logue, J.M (2012). Equivalence in Ventilation and Indoor Air Quality. HVAC&R Research, 18(4):760-773. LBNL-5036E.
52. Stetiu, S. (1999). Energy and peak power savings potential of radiant cooling systems in US commercial buildings. Energy and Buildings, 30(2):127-138.
53. U.S DOE. (2017). Global Energy Storage Database. US. Department of Energy: Washington D.C.
54. U.S. Energy Information Adminisitration. (2016). Consumption and Efficiency. US EIA. Retrieved from https://www.eia.gov/consumption/.
55. U.S. Environmental Protection Agency. (2013). Electricity Customers available: https://www.epa.gov/energy/electricity-customers/.
56. Wang, W., Katipamula, S., & Taasevigen, D.J. (2015). Part-load Performance Characterization and Energy Savings Potential of the RTU Challenge Unit: Carrier Weather Expert. PNNL-24480.
57. Watson, D.S., Kiliccote, S., Motegi, N., and Piette, M.A. (2006). Strategies for Demand Response in Commercial Buildings. Proceedings, 2006 ACEEE Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA, August. LBNL-60616.
58. Xu, P., Haves, P., Piette, M.A., and Braun, J.E. (2004). Peak Demand reduction from pre-cooling with zone temperature reset in an office building. 2004 ACEEE Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA, August. LBNL-55800.
59. Yin, R. Peng, X., Piette, M.A., and Kiliccote, S. (2010). Study on Auto-DR and pre-cooling of commercial buildings with thermal mass in California. Energy and Buildings, 42(7):967-975.
60. Yin, R., Kara, E., Li, Y., DeForest, N., Wang, K., Yong, T., and Stadler, M. (2016). Quantifying flexibility of commercial and residential loads for demand response using setpoint changes. Applied Energy, (177):149-164.
61. Yoon J.H., Bladick, R., & Novoselac, A. (2014). Demand response for residential buildings based on dynamic price of electricity. Energy and Buildings, (80):531–541.

Appendix A. Previous studies of demand response using building HVAC systems

Fernandez et al. (2017) conducted a study which estimated potential peak load reduction in commercial buildings using EnergyPlus and a strategy of retuning to detect, diagnose, and correct operational problems with building systems. It was found that four measures (demand-controlled ventilation, daylighting control, minimum VAV terminal box damper position, and wider dead bands and night setbacks) produced greater than 10% peak annual electricity demand reduction in at least one building type.

Hao et al. (2017) examined transactive control of a single mixed use building for demand response. They simulated a market-based control strategy where HVAC power was capped at a limit of 10% below the peak demand of the baseline. They found this approach to capable of providing a 6.1%-6.3% reduction in peak load.

Xu et al. (2004) tested an office environment where indoor air temperature was maintained at a lower bound during non-peak hours but allowed to fluctuate to the upper bound during peak hours of 2pm-5pm, which resulted in a chiller power demand reduction ranging between 1.0 and 2.3 W/ft^2. The first strategy was a pre-cooling + zonal reset strategy and the second strategy was an extended pre-cooling + zonal reset strategy. The building was an 80,000 ft^2 office building in Santa Rosa, CA.

Yin et al. (2010) implemented an optimal pre-cooling strategy in 11 office buildings and found electric demand during peak period was reduced between 0.20-1.13 W/ft^2. The climate zone was described a hot climate zone in California. Of the four pre-cooling strategies tested, the optimal started was a pre-cooling with linear temperature reset.

Watson et al. (2006) tested demand response strategies over three years in 28 commercial facilities. Demand response strategies (i.e. global temperature adjustment, fan control, chiller control, lighting, etc.) provided an average demand saving intensity of 0.5 W/ft^2. The authors also note that demand response HVAC strategies provided considerably greater savings on hotter days.

Kiliccote & Piette (2005) investigated control technologies and strategies linking demand response and energy efficiency. Their work at the Demand Response Research Center (DRRC) tested automated equipment control strategies at 18 sites in California, Wisconsin and Canada. The strategies involved both lighting controls (demand limiting, lighting sweep, overrides) and HVAC controls (equipment lockout, pre-cooling, thermal energy storage, cooling reduction, fan/pump/chiller quantity reduction). They found an average peak load reduction of 0.30 W/ft^2 across test on four days. However, it is noted that 9/8 was the only hot day, and its test resulted in an average peak load reduction of 0.67 W/ft^2.

Piette et al. (2007) conducted a pilot study of critical peak pricing (CPP) fully-automated demand response (Auto-DR) strategies for 24 commercial facilities that included office buildings, retail chain stores, museums, laboratory buildings, a museum, and a bakery. Most of the demand response strategies were HVAC strategies, and they were implemented during a 6-hour CPP time frame from 12pm-6pm. However, 12pm-3pm was designated as a moderate-price period and 3pm-6pm was designated as a high-price period. In examining, five of the 15 CPP event days the authors report average savings of 0.5 W/ft^2 and 0.72 W/ft^2 for moderate- and high-price periods, respectively.

Gu & Raustad (2001) simulated the effect of short-term curtailment of HVAC loads in office and retail buildings of different sizes in multiple climates. They suggest that a combination of two or more control strategies could yield peak demand (2pm-5pm) reductions ranging from 12% to 34%, depending on building type and HVAC system. With respect to ventilation, implementation of fan speed control for variable air volume systems resulted in a peak demand reduction of 12%. Small Offices across the climate zones had summer load reductions ranging from ~25% to 32%. Medium Offices across the climate zones had summer load reductions ranging from ~21% to 30%; we found load reductions up to 16%. Large Offices across the climate zones had summer load reductions ranging from ~20% to 27%. Retail stores across the climate zones had summer load reductions ranging from ~29% to 41%.

Lee & Braun (2008) tested a weighted average demand limiting strategy in a California bank (11,000 ft^2), during the peak period (12pm-6pm) and found a four-day average peak power savings of 0.76 W/ft^2. The test was conducted at a small bank building in Palm Desert, CA.

During an earlier study, Lee & Braun (2006) evaluated demand limiting through use of building thermal mass and setpoint schedule shifting during a peak period (1pm-6pm). They tested a demand limiting strategy with and without occupied cooling and found peak demand reductions of 2.7 W/ft^2 and 1.7 W/ft^2, respectively. The testing was done in the energy resources station in Ankeny, Iowa (ASHRAE climate zone 5A).

Khanolkar, Reddy, and Addison (2013) simulated the effect of short-term notification demand response measures in Medium and Large Office buildings in Phoenix, AZ during peak demand (2pm-6pm). The demand response strategies included lighting power density reduction, thermostat set-point setback, supply air temperature adjustment, and chilled water temperature reset. They found that demand response management can give up to a 25% peak load reduction in Large Office buildings and Medium Office buildings. Furthermore, it was found that thermostat set-point setback gave the highest individual load reduction (18% in Large Office and 23% in Medium Office).

Li & Xu (2016) evaluated two demand response strategies (via simulation and field study) in a government office building (80,000 ft^2) located in Santa Clara, CA (ASHRAE climate zone 3C). The first strategy was a pre-cooling + zonal reset strategy and the second strategy was an extended pre-cooling + zonal reset strategy. On warm days, the first strategy showed test and simulation peak load decreases of 1.15 W/ft^2 and 1.12 W/ft^2, respectively. The second strategy showed test and simulation peak load decreases of 1.24 W/ft^2 and 1.13 W/ft^2.

Parmenter et al., (2008) simulated demand response strategies for an office building, specifically looking at lighting reduction, and manually increasing the cooling setpoint during a demand response event. These strategies yielded a 15% reduction in peak power demand during the three warmest weekdays of the summer (July 29-31) between the hours of 2pm and 5pm.

Kiliccote, Piette, and Watson (2006) looked at dynamic controls for demand response using global setpoint adjustment and, lighting, increasing supply air temperature, and reducing the capacity of fans. They simulated these dynamic controls using a model of *The New York Times* headquarters (74,000 ft^2, ASHRAE climate zone 4A) and found potential demand reduction between 0.9 W/ft^2 and 1.4 W/ft^2.

Stetiu (1999) tested the effect that a radiant cooling system instead of an all-air system has on peak power demand in medium office buildings. The study simulated peak power trends across many climates and found savings ranging from 0.7 W/ft^2 in New York, NY to 1.7 W/ft^2 in Phoenix, AZ.

Roussac & Huang (2018) studied the reduction of peak demand in commercial buildings in Melbourne and Sydney. They used model that accurately predicted building electricity demand for a 15-minute period, up to five days in advance. When peak demand days were upcoming, they would engage building operators in a “peak demand action plan”. Some of the measures included raising global temperature setpoints, turning down air handling unit pressure setpoints, adjusting lighting, and raising chilled water temperature setpoints. Operators were able to shave an average of 0.3 W/ft^2 from their buildings’ peak demand.

Appendix A. Detailed model inputs

Model inputs for residential buildings are given in Tables B1 and B2.

Element	***Prototype 1***	***Prototype 2***
Ceiling height (ft)	9	9
Conditioned Floor Area (ft^2)	2,100	2,700
Conditioned Volume (ft^3)	18,900	25,750
Gross Areas		
Slab (ft^2)	2,100	1,250
Slab perimeter, outside (ft^2)	162	128
Slab perimeter, garage (ft^2)	30	30
Ceiling (ft^2)	2,100 unvented attic	1,450 unvented attic
Roof slope (%)	20	20
Roof Deck R-value	R13 (airspace) below deck insulation, in CZ4 and 8-16	
Ceiling Insulation	R38 (R30 in CZ3, 5, 6 and 7)	
Radiant Barrier	No	No
Wall U-value	0.051 (0.065 in CZ6&7)	0.051 (0.065 in CZ6&7)
Slab Perimeter R-value	0 (7 in CZ16)	0 (7 in CZ16)
Window U-value	0.32	0.32
Window SHGC	0.25	0.25
Window Area	20% floor area	20% floor area
Gas Furnace AFUE	92%	92%
AC SEER	16	16

Table A.1 Model input values for prototype homes

CEC CZ	**Air Handler Fan Efficacy (W/cfm)**	**Air Handler Flow Rate (cfm)**	**Rated Total Cooling Capacity (W)**	**Rated Cooling COP (W/W)**	**Gas Heater Nominal Capacity (W)**	**Gas Burner Efficiency AFUE**
1	0.365	593	5275	3.95	7033	0.92
3	0.365	593	5275	3.95	7033	0.92
10	0.402	996	8792	3.95	7033	0.92
16	0.365	805	7034	3.95	7033	0.92

Table A2. HVAC system variables for each climate region.

Appendix B. Power shed available by climate in all building types
The potential for peak demand shed through ventilation curtailment in commercial buildings will vary both by building type, and by climate. Different building types will require different volumes of outdoor air and ventilation flow rates, largely based on their occupant densities. Higher density buildings (Schools and Retail Stores) still perform the best across all climate zones but perform exceptionally well in hot (ASHRAE climate zones 1-3) and humid (ASHRAE climate zone A) climates. Conversely, colder coastal climates, such as San Francisco, CA (ASHRAE climate zone 3C) or Anchorage, AK (ASHRAE climate zone 8) showed minimal demand reductions or even increases in power demand when ventilation was completely curtailed. The percentage for how much each building type can save with complete ventilation curtailment will also change based on climate zones. The results for complete curtailment from 2pm-6pm during the hottest days of the year for each building type can be found below.

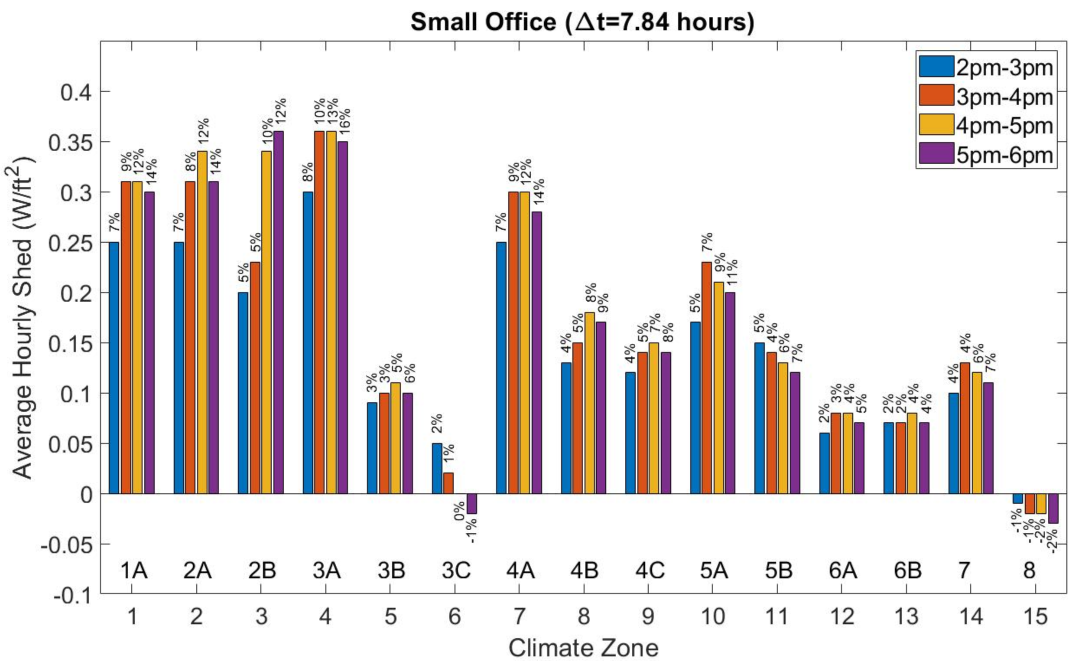

Figure B.1 Power demand shed over a 4-hour ventilation curtailment during peak hours (2pm-6pm) for 10 of the hottest weekdays of the TMY3 for Small Offices in 15 different ASHRAE climate zones

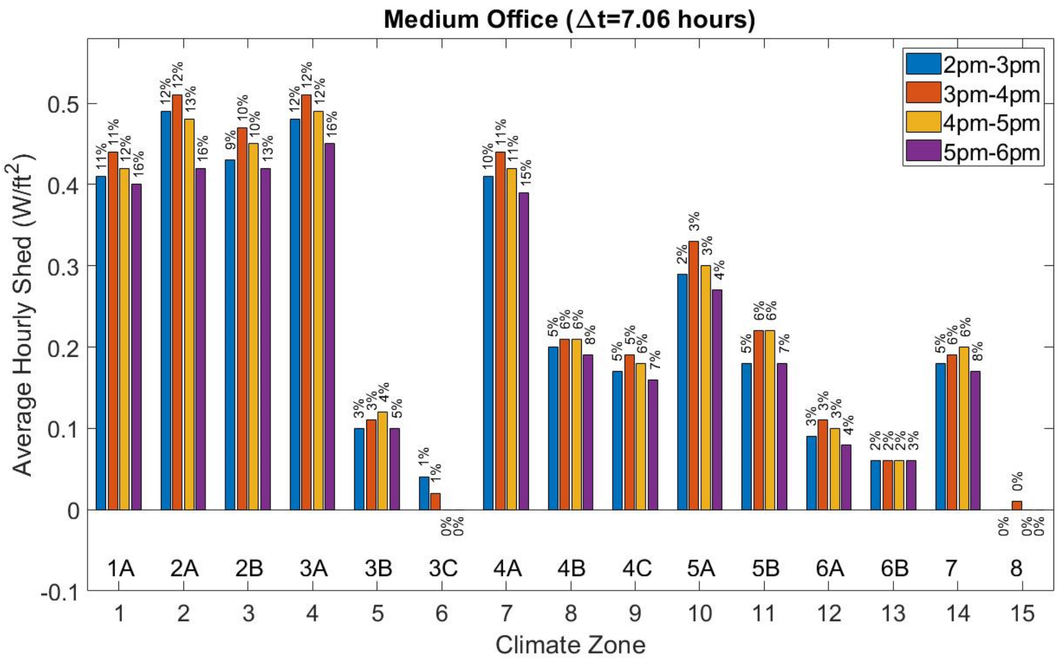

Figure B.2 Power demand shed over a 4-hour ventilation curtailment during peak hours (2pm-6pm) for 10 of the hottest weekdays of the TMY3 for Medium Offices in 15 different ASHRAE climate zones

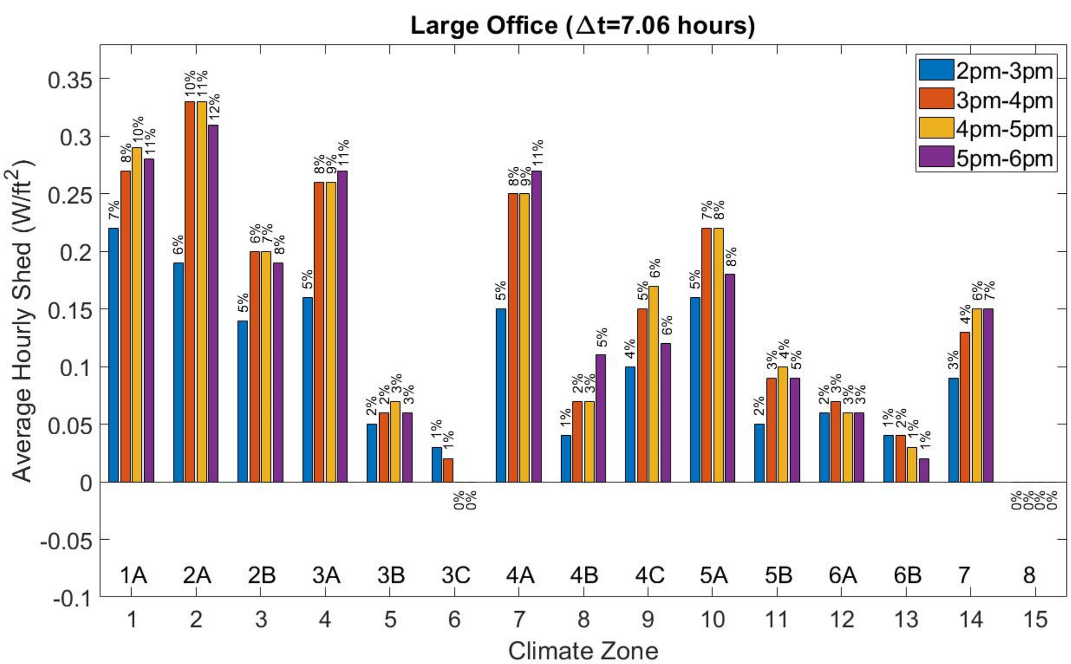

Figure B.3 Power demand shed over a 4-hour ventilation curtailment during peak hours (2pm-6pm) for 10 of the hottest weekdays of the TMY3 for Large Offices in 15 different ASHRAE climate zones

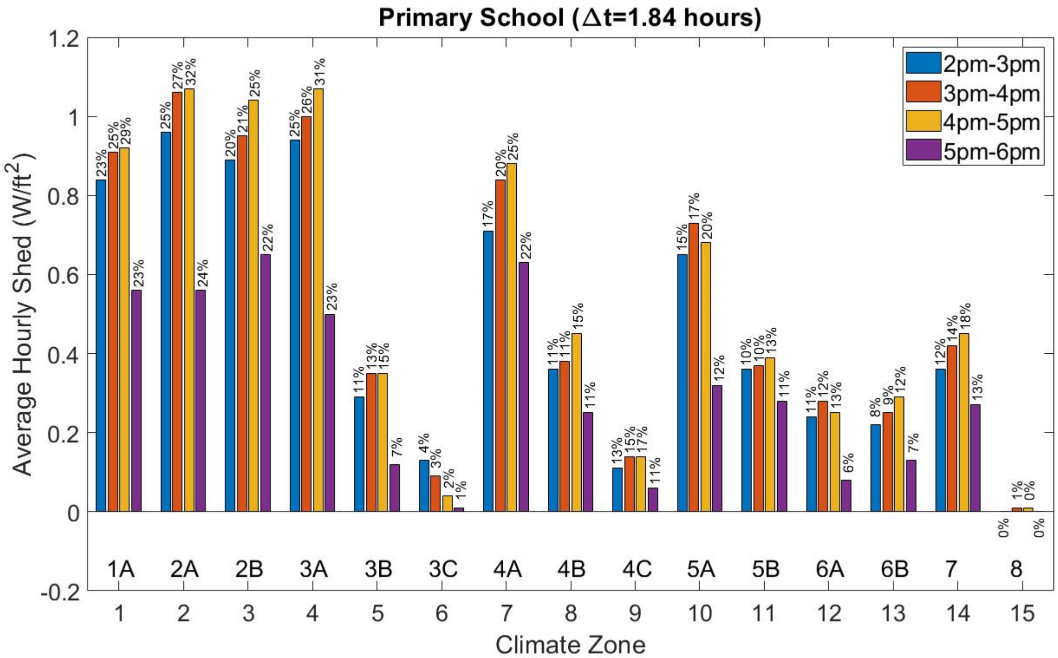

Figure B.4 Power demand shed over a 4-hour ventilation curtailment during peak hours (2pm-6pm) for 10 of the hottest weekdays of the TMY3 for Primary Schools in 15 different ASHRAE climate zones

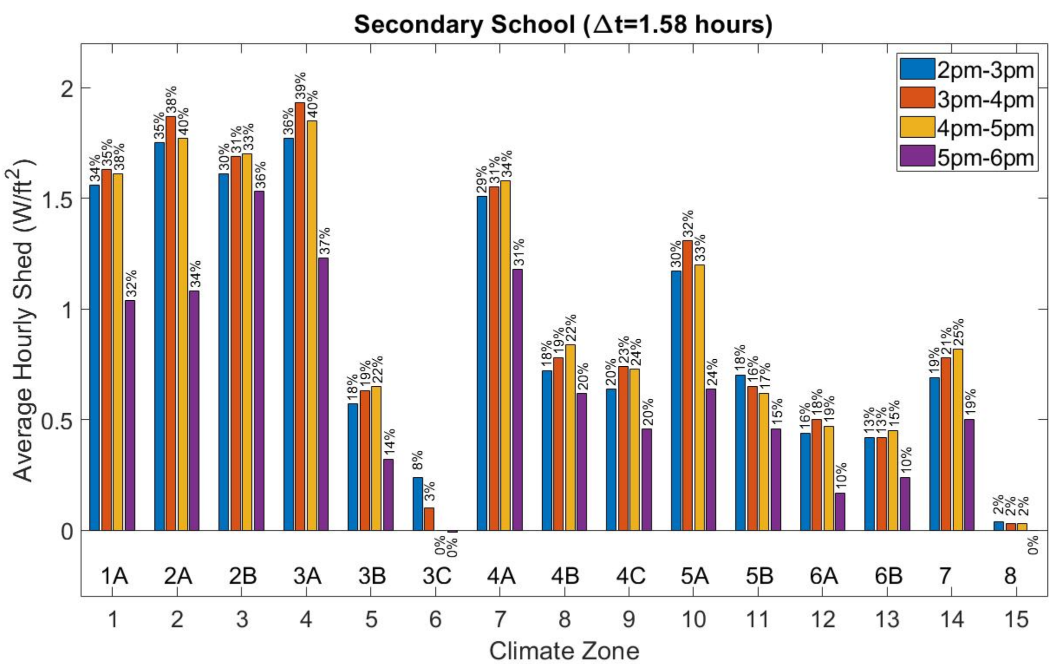

Figure B.5 Power demand shed over a 4-hour ventilation curtailment during peak hours (2pm-6pm) for 10 of the hottest weekdays of the TMY3 for Secondary Schools in 15 different ASHRAE climate zones

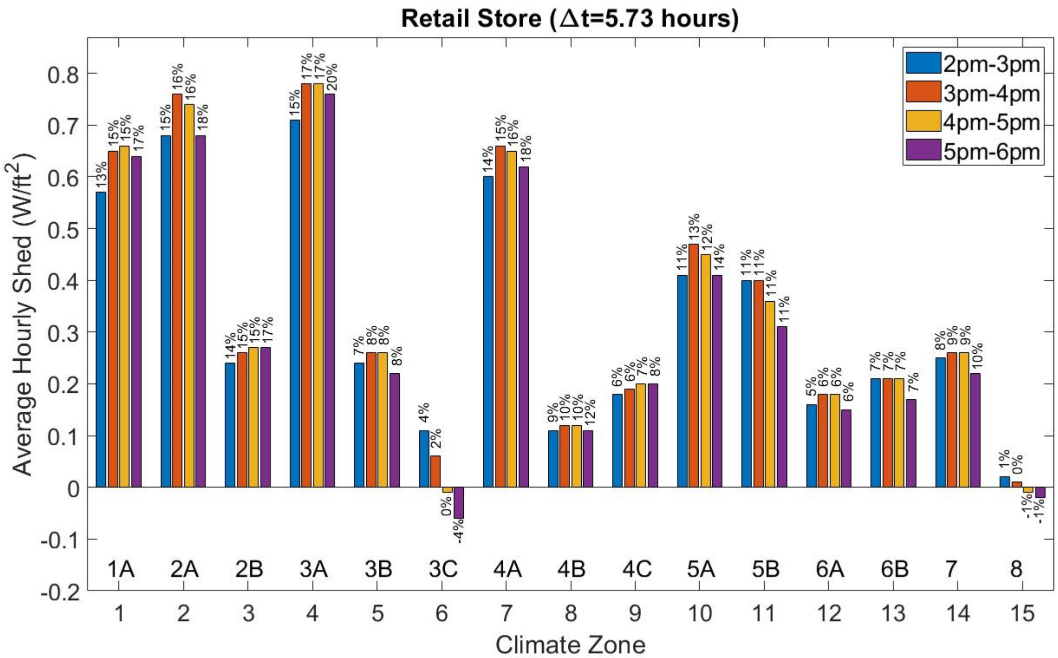

Figure B.6 Power demand shed over a 4-hour ventilation curtailment during peak hours (2pm-6pm) for 10 of the hottest weekdays of the TMY3 for Retail Stores in 15 different ASHRAE climate zones

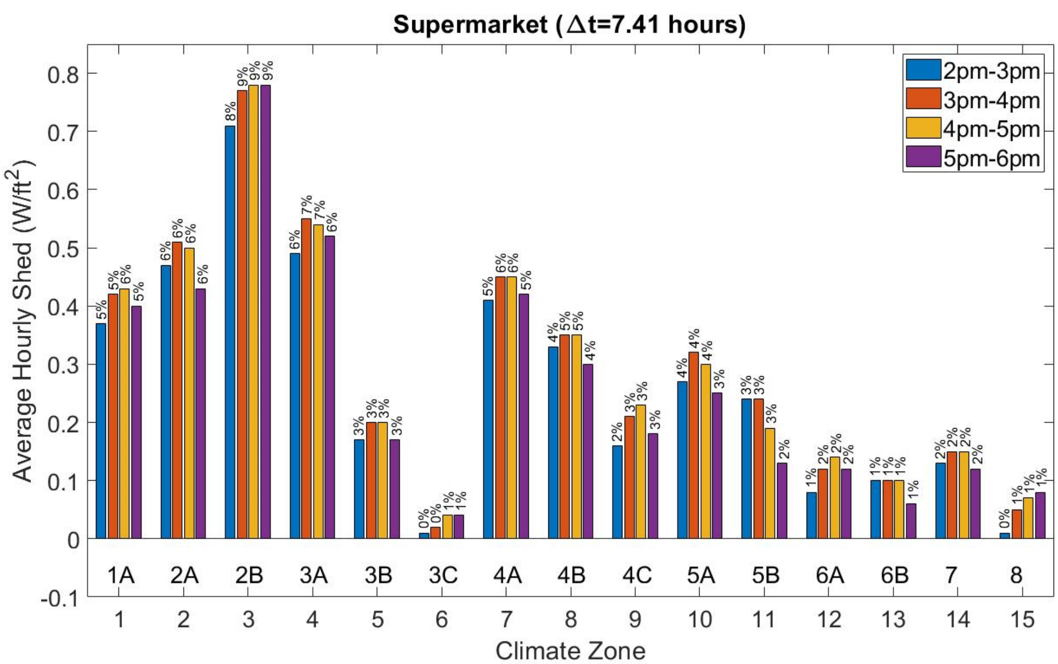

Figure B.7 Power demand shed over a 4-hour ventilation curtailment during peak hours (2pm-6pm) for 10 of the hottest weekdays of the TMY3 for Supermarkets in 15 different ASHRAE climate zones

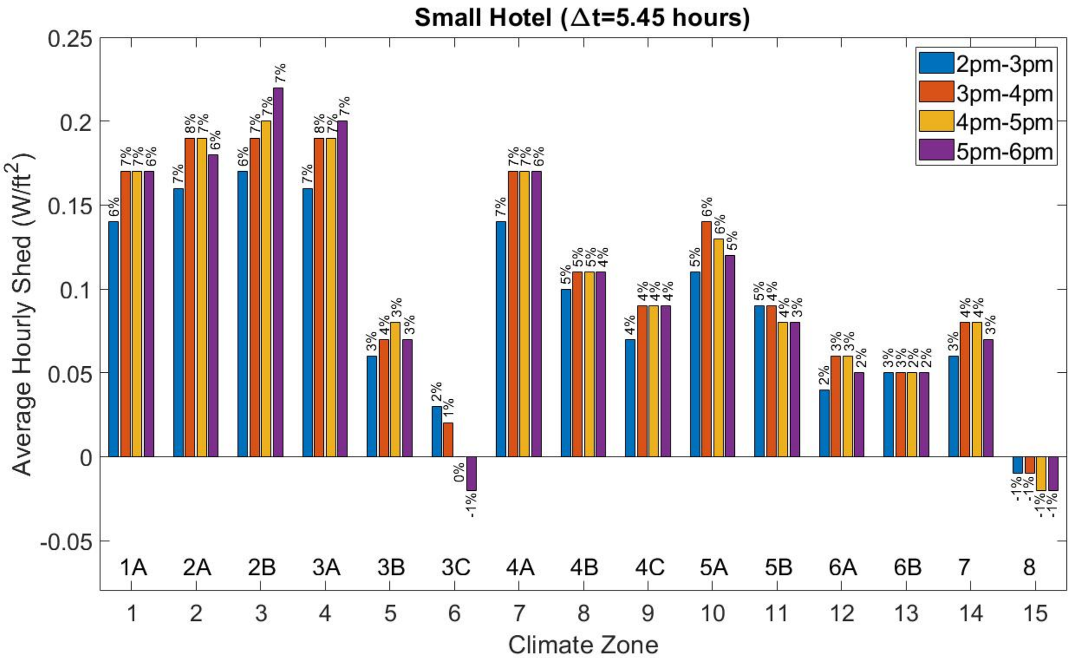

Figure B.8 Power demand shed over a 4-hour ventilation curtailment during peak hours (2pm-6pm) for 10 of the hottest weekdays of the TMY3 for Small Hotels in 15 different ASHRAE climate zones

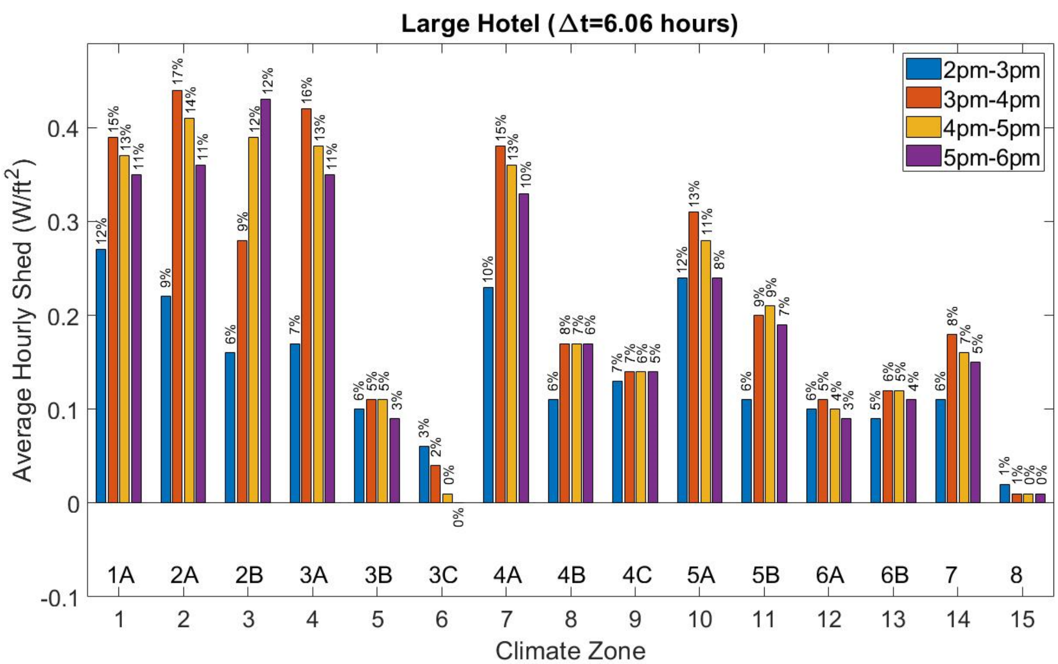

Figure B.5 Power demand shed over a 4-hour ventilation curtailment during peak hours (2pm-6pm) for 10 of the hottest weekdays of the TMY3 for Large Hotels in 15 different ASHRAE climate zones