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Residential precooling on a high-solar grid: impacts on CO_2 emissions, peak period demand, and electricity costs across California

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Abstract

As regional grids increase penetrations of variable renewable electricity (VRE) sources, demand-side management (DSM) presents an opportunity to reduce electricity-related emissions by shifting consumption patterns in a way that leverages the large diurnal fluctuations in the emissions intensity of the electricity fleet. Here we explore residential precooling, a type of DSM designed to shift the timing of air-conditioning (AC) loads from high-demand periods to periods earlier in the day, as a strategy to reduce peak period demand, CO_2 emissions, and residential electricity costs in the grid operated by the California Independent System Operator (CAISO). CAISO provides an interesting case study because it generally has high solar generation during the day that is replaced by fast-ramping natural gas generators when it drops off suddenly in the early evening. Hence, CAISO moves from a fleet of generators that are primarily clean and cheap to a generation fleet that is disproportionately emissions-intensive and expensive over a short period of time, creating an attractive opportunity for precooling. We use EnergyPlus to simulate 480 distinct precooling schedules for four single-family homes across California's 16 building climate zones. We find that precooling a house during summer months in the climate zone characterizing Downtown Los Angeles can reduce peak period electricity consumption by 1–4 kWh d^{-1} and cooling-related CO_2 emissions by as much as 0.3 kg CO_2 d^{-1} depending on single-family home design. We report results across climate zone and single-family home design and show that precooling can be used to achieve simultaneous reductions in emissions, residential electricity costs, and peak period electricity consumption for a variety of single-family homes and locations across California.

1. Introduction

In the building sector, precooling refers to an air-conditioning (AC) operation strategy where the AC is used to overcool a space for a period of time in efforts to reduce cooling needs at a later time. Because precooling can effectively shift some electricity demand from one time period to another by using the thermal storage properties of the building itself, it has gained interest as an attractive application for demand response (DR), a subgroup of demand-side management (DSM) strategies designed to shift the magnitude or timing of electricity demand on the end-user side of electricity meters [1]. A key component of DR, compared to other DSM strategies, is its focus on incentivizing end-users to temporarily adjust the timing of their daily electricity consumption from one period to another rather than simply reducing the magnitude of their total consumption [2].

Precooling is a particularly attractive DR application in grids with high solar generation, since AC can be used more aggressively when solar resources and daytime temperatures are highest, and then relaxed when more emissions-intensive generation (e.g. natural gas and imports) is needed to be quickly dispatched to replace lost solar generation. As the mix of resources servicing the grid changes over the course of a day, so do the per-unit emissions associated with consuming electricity [3–6]. Solar availability varies diurnally, seasonally, and climatically, and, in the absence of grid-scale storage, electricity from variable resources must be consumed instantaneously or curtailed. Therefore, strategies like precooling that can shift the timing of electricity consumption from fossil-fuel dominated hours to renewable energy dominated hours could theoretically achieve reductions in CO_2 emissions by reducing solar curtailment and/or lowering the average emissions intensity of the electricity, even if the total amount of electricity consumed does not change or increases by a moderate amount.

As load shifting and DR strategies become increasingly important for grid operators attempting to manage peak demand, it is important to evaluate the effectiveness of precooling as a peak demand- and cost-reducing strategy for a wide variety of home types and climatic conditions. Growing penetrations of renewable energy in regional grids, like the one overseen by the California Independent System Operator (CAISO, which covers 80% of California's [7] bulk power transmission), also present an emerging opportunity to compound these benefits through CO_2 emissions reductions. CAISO reached a peak 5 min solar penetration of 72% of total load on a day in 2022 [8] and in 2021 over a third of annual in-state generation in California was sourced from renewable power, with 17.1% coming from solar power [9].

Here we use EnergyPlus to simulate the cooling-related energy demand, CO_2 emissions, and utility bill costs associated with 480 unique residential precooling schedules for four distinct single-family home designs in each of California's 16 climate zones (spanning the area covered by CAISO). These four buildings have distinct thermal mass and envelope characteristics and span a wide range of performance levels so that we can evaluate the ability of precooling to deliver simultaneous reductions in residential electricity costs, peak period electricity demand in California, and cooling-associated CO_2 emissions, and examine the trade-offs when prioritizing reductions in one of the variables of interest for a variety of conditions. We chose CAISO as a case study because of its high mid-day solar penetration, which makes it an interesting case study to evaluate if precooling is an effective tool for mitigating growing challenges related to peak demand management as high quantities of solar generation are replaced by quick-ramping natural gas generators in the early evening as the Sun goes down. This study provides novel analysis on precooling's ability to reduce emissions on a high solar power grid using marginal emissions factors (*MEF*s), which are better suited for demand-side interventions than average emissions factors (*AEF*s).

2. Literature review

The load-shifting potential of precooling varies according to a building's thermal mass, which is defined as its ability to store energy [10]. In the event of a difference between the indoor and outdoor temperature, the thermal inertia of buildings slows the rate at which the indoor temperature approaches the outdoor temperature. Precooling has been studied extensively in the commercial sector for buildings of high thermal mass, and more recently has been explored for lower-mass residential buildings. In the commercial sector, Keeney and Braun [11] performed one of the first precooling studies by precooling a large office building overnight, and achieved reductions in max demand for cooling electricity and operational cost while maintaining thermal comfort. Braun *et al* [12] simulated a building in Santa Rosa, CA and found that over 80% of on-peak load could be shifted to an off-peak period with precooling. Xu *et al* [13] extended this study using the building simulation software EnergyPlus to explore a larger number of scenarios and confirmed precooling's ability to shift load for large commercial buildings.

Because homes have a limited amount of thermal mass and ability to retain energy compared to larger buildings, precooling must occur in close proximity to the period in which reduced cooling demand is desired, limiting the temporal flexibility of residential precooling. Hence, most residential sector studies explore precooling in the middle of the day or early afternoon to reduce late-afternoon and evening electricity demand, which shifts AC demand away from periods of high grid-level demand and aligns well with typical time-of-use (TOU) rate plans that charge more for electricity during peak demand periods. Numerous studies in the residential sector have confirmed precooling's ability to reduce electricity bills for customers exposed to TOU electricity rates [14–23]. Wang *et al* [14] developed a linear programming method capable of determining the optimal precooling schedule for a specific building and determined that cost-optimized schedules could reduce costs by as much as 56% when compared to rule-based cooling schedules. Nelson *et al* [18] used EnergyPlus to simulate precooling a building in multiple climate zones and found cost reductions as high as 23.5% were possible in Phoenix, AZ, although the savings in Los Angeles, CA, were found to be just 1.7%. The reduced benefits in Los Angeles may be the result of a more temperate annual climate or a consequence of less aggressive local utility TOU rates. The ability of precooling to reduce demand during a predefined peak period has also consistently been confirmed in the residential sector [14–18, 21–25]. Cole *et al* [21] used a building simulation software to explore the efficacy of precooling a home in Austin, Texas during the months of July and August, during which precooling successfully reduced peak energy consumption by an average of 70%. Turner *et al* [25] explored precooling across twelve distinct

US climate zones, and found that at least 50% of annual cooling consumption can be shifted away from a peak period in every zone.

While precooling has been shown to reduce both residential electricity costs and peak period electricity consumption, a number of factors have been shown to influence the potential reductions, including the building's thermal mass and envelope characteristics [17, 19, 22, 23, 25–29], which influence its ability to maintain its temperature, and the location or climate zone the building is located in [15, 17, 18, 22]. For example, in [25] all locations realized peak load reductions of greater than 50%, but some climate zones were able to reduce peak load by as much as 99% by precooling, and the increase for total cooling electricity consumption needed to achieve these peak period reductions varied greatly, though building envelope properties were not held constant between locations. German and Hoeschele [17] used EnergyPlus to simulate a building in seven different U.S. cities and found that reductions in peak period electricity consumption varied from near zero to near 50%. Herter Energy Research Solutions [23] tested precooling using occupied residential buildings in the Sacramento, California area and recommended a minimum ceiling R-value of 38 in order to effectively shed evening load while maintaining thermal comfort and minimizing any penalties in total electricity consumption. Several studies have explored modern wall materials and insulation techniques to determine their impact on precooling, including Wijesuriya *et al* [27], who studied phase change material (PCM) enhanced drywall; Kishore *et al* [28], who also studied PCM-integrated walls; and Dehwah and Krarti [29] who explored precooling in a home with switchable insulation systems. The results of these residential precooling studies show that precooling's effectiveness is difficult to generalize because the specific building properties and location need to be considered.

While the impact of precooling on peak period electricity consumption and residential electricity bills has been well-researched, the influence of precooling on CO_2 emissions has received significantly less attention. Mayes and Sanders [30] simulated a single-family residential building prototype in the Climate Zone that includes Los Angeles, CA, and calculated the resulting CO_2 emissions using *AEF*s for the CAISO region. They found that precooling can reduce CO_2 by 3%–4% when compared to a constant setpoint schedule via leveraging the large diurnal variations that exist in CAISO grid's emissions intensity in daytime versus evening hours. Stopps and Touchie [31] examined precooling for high-rise residential buildings and calculated the impact on greenhouse gas emissions using *MEF*s for the grid in Toronto, Canada. Their study showed mixed results for precooling's ability to reduce peak demand depending on the specific unit in the high-rise, but even for units where peak demand was reduced, they did not find significant or consistent greenhouse gas emissions reductions despite the large diurnal variations in *MEF*s for this region caused by the varying mix of hydropower and natural gas on the margin. Unlike many residential precooling studies, this study focused on overnight and morning precooling, the times when the local grid's marginal resources were the cleanest.

3. Methodology

3.1. Single-family home selection

The single-family residential homes used in this study come from the National Renewable Energy Lab's (NREL) ResStock model [32]. NREL developed a large set of residential prototypes designed to represent the spread of buildings present in the residential sector across the country. These prototypes are created via permutations of a large number of building properties, and are designed to be region-specific. In total, the ResStock model has 549 871 residential building designs available for download [33]. The four single-family selected from this database contain many common values in order to increase the comparability of results (finished area, no pool, central air conditioning, window types, slab foundation, natural gas heating, etc) but have differences in key insulation and AC properties. The single-family homes span a range of wall (none to R-19) and ceiling (R-13–R-49) insulation levels as well as a range of AC efficiency levels (SEER 10 to SEER 13). Key building properties can be found in appendix A.1, and the full list of building properties can be found in the online data repository (https://data.mendeley.com/datasets/333jfmpvb8/1).

The variation in these parameters provides a spread of results that show the impacts of building envelope and AC efficiency on the variables of interest. At opposite ends of the spectrum, Building 1 (B1) represents a poorly insulated single-family home with low AC efficiency and Building 4 (B4) represents a well-insulated single-family home with high AC efficiency. Considering that these prototypes were developed to represent actual homes, we treat Buildings 1 and 4 as representing a reasonable low- and high-end of performance levels for the existing single-family California building stock (with Buildings 2 and 3 falling in-between these extremes). We label these homes B1 through B4 in figures when relevant.

Table 1. Summary of California's climate zones [36].

Climate Zone	Reference city	CDDs	Warmest month (Max, Mean, Min T in °F)
CZ1	Eureka	15	September (62, 57, 51)
CZ2	Napa	500	August (82, 67, 51)
CZ3	Oakland	183	September (73, 65, 57)
CZ4	San Jose	666	July (82, 70, 58)
CZ5	Santa Maria	464	September (74, 63, 51)
CZ6	Los Angeles (LAX)	742	August (76, 70, 63)
CZ7	San Diego	865	September (62, 58, 51)
CZ8	Long Beach	1072	August (83, 73, 62)
CZ9	Los Angeles (Downtown)	1456	August (83, 74, 65)
CZ10	Riverside	1620	August (94, 78, 60)
CZ11	Red Bluff	1354	July (98, 82, 67)
CZ12	Stockton	1226	July (95, 77, 59)
CZ13	Fresno	1599	July (98, 81, 63)
CZ14	Barstow	3056	July (102, 84, 67)
CZ15	Brawley	4760	July (107, 91, 76)
CZ16	Bishop	596	July (97, 77, 56)

Table 2. Definitions of precooling-related terms used in this study.

Term	Significance	Units
Peak Period	Period during which CAISO experiences high demand, defined as 4–9 pm (also common hours for Flex Alerts [37])	Twelve-hour clock range
Precooling Period	The portion of the day during which precooling occurs (AC setpoint below baseline temperature)	Twelve-hour clock range
Offset Period	Three-hour period immediately after precooling, always falls within the Peak Period (AC setpoint above baseline temperature)	Twelve-hour clock range
Start Time	Time of day at which transition from precooling period to offset period occurs	Twelve-hour clock time
Baseline Temperature	Temperature at which house is kept outside of the precooling and offset period	°F
Length	Duration of the precooling period	Hours (h)
Depth	Number of degrees below the baseline temperature the AC is set at during the precooling period	°F
Offset Temperature	Number of degrees above the baseline temperature the AC is set at during the offset period	°F
Reset Method	Method of returning to baseline temperature at the end of the offset period	1: Setpoint returns instantly (sudden) 2: Setpoint returns linearly over two hours (gradual)

3.2. Weather files

The weather files used in this study were downloaded from the EnergyPlus website [34] and represent a typical meteorological year (over a 30 year period) for each of the 16 California Building Climate Zones, as specified by the Climate Design Data 2009 ASHRAE Handbook. The climate zones were defined as part of California's Title 24 Building Energy Efficiency Standards [35]. Each zone describes a unique geographic area in California and has its own set of Title 24 requirements for ceiling and wall insulation and window u-values [36]. The reference city for each zone and a brief description of its characteristics are included in table 1.

These climate zones span a large range of cooling degree-days (CDDs), and hence, a large range of potential cooling needs (CDDs range from climate zones that typically have fewer than 50 annual CDDs to zones that have 4000–6000 annual CDDs).

3.3. Precooling schedules

Precooling schedules typically feature a time period where the AC setpoint is below a baseline temperature, closely followed by a period where the AC setpoint is above the baseline temperature. In this study we define and refer to specific precooling schedules with the terms specified in table 2 and illustrated in figure 1.

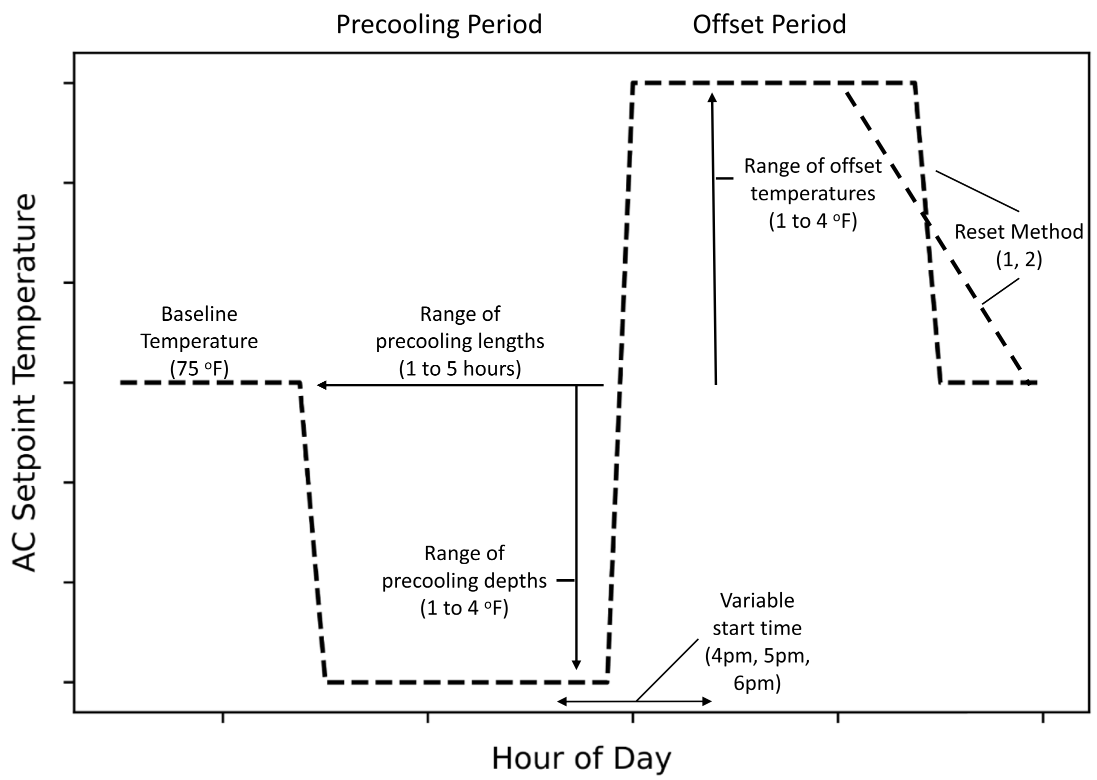

Figure 1. Theoretical precooling schedule with illustration of key terms from table 2.

To define the full set of precooling schedules, we vary the precooling length from 1 to 5 h, the depth from 1 °F to 4 °F (0.56 °C–2.22 °C), the offset temperature from 1 °F to 4 °F (0.56 to 2.22 °C), the start time from 4 to 6 pm, and the reset method through both of its options. We restrict the ranges for precooling depth and offset temperature to 4 °F (2.22 °C) to avoid creating exceedingly uncomfortable conditions, as discussed further in sections 3.5 and 5.1, and due to computational limitations. Possible values are restricted to integer values, and these permutations create a total of 480 distinct precooling schedules to test for each single-family home design/climate zone combination. Precooling length, depth, and offset temperature, are restricted to integer values to represent schedules that can be easily employed by homeowners, given that most thermostats by default take integers for their setpoints, and sub-hourly adjustments in temperature are impractical for those without high-tech smart thermostats. The large number of tested schedules provides a broad domain from which to select a schedule that reduces a variable of interest. The baseline cooling schedule uses a constant setpoint of 75 °F (23.89 °C) at all hours of the day and serves as a reference point with which the precooling schedules are compared.

3.4. EnergyPlus simulation

Simulations of each precooling schedule are done using EnergyPlus, a building energy simulation software developed by the Department of Energy [38]. EnergyPlus has been tested and verified both internally and externally, with relevant studies listed on the EnergyPlus website [39]. EnergyPlus has been used both directly and indirectly (through programs that make use of the EnergyPlus engine or results) for a number of precooling studies in both the residential and commercial sector due to its ability to explore a large number of alternatives in a time-efficient manner [16–18, 21, 24, 27, 29, 40–42]. For each EnergyPlus simulation, we input a modified data file from the ResStock project that specifies the home's properties and AC setpoint schedule, as well as a weather file that describes one typical year of weather in the climate zone in question. We simulate each single-family home using all of the precooling schedules and the baseline schedule in each of California's building climate zones (a total of 30 784 simulations). EnergyPlus returns information at the hourly level, including indoor and outdoor climatic variables and electricity consumption—the main output used for the analysis of the precooling schedules.

3.5. Thermal comfort

An occupant's thermal comfort is an important consideration when analyzing the effect of a precooling schedule. Thermal comfort describes a person's perceived thermal sensation and can be estimated with a large set of methods and metrics [43]. Several previous precooling studies [11, 24, 25, 30, 44, 45] have made use of Predicted Mean Vote (PMV), a thermal comfort metric developed by Fanger [46]. The PMV metric is designed to estimate the self-described mean sensation of a large group of people based on variables such as current temperature, humidity, wind speed, activity level, and clothing level. In the PMV model, thermal comfort is measured on a seven point scale (centered at a neutral sensation, PMV = 0), and The American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) defines an acceptable range for PMV as −0.5 to +0.5 [47].

In this study, standard values were used for wind speed (0.1 m s^{-1}), activity level (1.1: seated, typing), and clothing level (0.5, typical summer indoor clothing), while temperature and relative humidity were reported hourly by EnergyPlus. The baseline temperature of 75 °F (23.89 °C) was selected because it provides a close to neutral mean PMV for the test period for building 4 (the best insulated home). For the homes with better insulation and higher AC efficiency, there is a close correlation between AC setpoint and actual indoor temperature, but for the more poorly insulated homes with less efficient AC the indoor temperature can significantly exceed the AC setpoint at a given time. In response, we use PMV to define a range of permissible AC setpoints by only allowing schedules that would fall in an acceptable comfort range assuming the indoor temperature matched the AC setpoint. Using constant values for the other variables, a PMV range of −0.5 to +0.5 translates to roughly a 6 °F (3.33 °C) range [48], reducing our precooling schedule space to schedules that use a precooling depth of no more than 3 °F (1.67 °C), and a maximum offset temperature of 3 °F (1.67 °C). This filter reduces our simulations from 480 per building-climate zone to 270, and our total simulations from 30 784 to 17 316. We discuss the impact of precooling on actual thermal comfort levels in the absence of this filter in section 5.1.

3.6. Output processing

Using the hourly electricity consumption values generated by EnergyPlus, we calculate the CO_2 emissions, residential electricity costs, and peak period electricity consumption for each precooling schedule as well as the baseline schedule, and repeat this process for each home design and climate zone. We restrict the analysis of these results to the months of July, August, and September due to the increased cooling needs during this summer period. Precooling schedules generally cause higher total daily electricity consumption than a constant setpoint schedule, with consumption increasing for longer and deeper precools, but we focus on the peak period when analyzing electricity consumption in this analysis and consider the total impacts on CO_2 emissions and residential electricity costs.

To determine the emissions associated with a precooling schedule, we use grid-level emissions factors calculated from historical data with linear regression models. Emissions factors generally quantify the amount of emissions associated with a unit of activity, in this case, the amount of CO_2 emissions associated with consuming a unit of electricity. Researchers typically draw a distinction between two types of emissions factors: *AEF*s and *MEF*s [49, 50]. *AEF*s describe the relationship between the total amount of emissions being produced by the grid and total supply of (or demand for) electricity; hence, they are useful for evaluating the emissions impacts of existing and regular electricity loads. *MEF*s, by contrast, describe the relationship between changes in emissions and changes in generation (or demand); hence, they are used for evaluating the impact of changes in the magnitude or timing of existing loads on emissions. *MEF*s are more applicable for load-shifting strategies like precooling, since these types of DR activities impose temporary changes in electricity-consuming behavior, prompting a temporary increase or decrease of marginal generation that would not occur if the DR strategy were not employed.

To calculate the emissions associated with a cooling schedule, we first use *AEF*s calculated at the month-hour resolution (*AEF* is specific to the month of the year and hour of the day) to determine the emissions from the baseline schedule, and then use month-hour *MEF*s to adjust these emissions for each precooling schedule depending on the difference in hourly electricity consumption between the precooling and baseline schedule. Equation (1) shows this calculation at the hourly level, and results for the full three-month simulation period are reported by summing the hourly results. This method treats the baseline cooling consumption as an existing/established load, and assumes that the changes in consumption caused by precooling are met by marginal generation. This distinction is consistent with recommended advice for using *AEF*s and *MEF*s in existing literature [5, 51].

$$CO2_{\mathrm{precooling,h}} = AEF_h \times e^{-}_{\mathrm{baseline,h}} + MEF_h \times \left(e^{-}_{\mathrm{precooling,h}} - e^{-}_{\mathrm{baseline,h}}\right). \quad (1)$$

Here e^{-} denotes the hourly consumption of electricity for cooling in kWh (with subscripts specifying the baseline or precooling schedule), *AEF* and *MEF* refer to the average and marginal emissions factor in $\frac{\mathrm{kgCO_2}}{\mathrm{kWh}}$ at a point in time, and the subscript h denotes a specific hour in the study period. The MEFs and AEFs used are specific to CAISO's grid, and are calculated following the methodology developed by Zohrabian *et al* [4] for

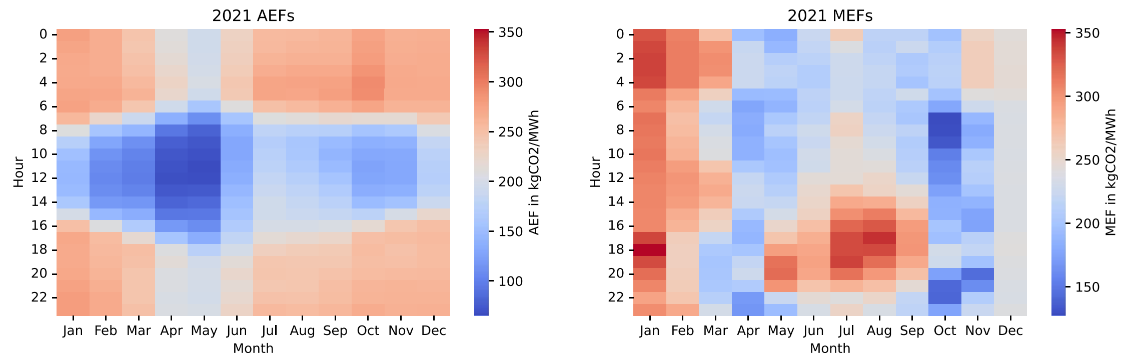

Figure 2. Month-hourly average (left) and marginal (right) Emissions Factors for the CAISO grid in 2021. Factors for the months of July, August, and September were included in this study.

the year 2021 and are shown in figure 2. This method was designed to develop MEFs that isolate the impact of demand on emissions, which is ideal for DSM applications such as precooling. The data used to calculate these AEFs and MEFs can be found in the online data repository (https://data.mendeley.com/datasets/333jfmpvb8/1) and additional notes on the AEF and MEF calculations can be found in section A.2.

Reductions in peak period electricity consumption are found by summing the daily electricity consumption between 4 and 9 pm for the baseline schedule and all of the precooling schedules. This time period includes the hours during which CAISO's grid typically reaches peak net load [52] (net load is defined as total demand minus variable renewable electricity (VRE) production). For peak period consumption and CO_2 emissions we report average daily values for the three-month study period.

The hourly residential electricity cost associated with a precooling schedule (C_h in $), as well as the baseline schedule, is calculated based on a selected hourly TOU rate schedule as shown in equation (2). Here r_h ($\frac{\$}{\text{kWh}}$) refers to the hourly price for residential electricity during a specific hour under the TOU plan.

$$C_h = r_h \times e_h^- . \tag{2}$$

In sections 4.1 and 4.2, we use a TOU program offered by Southern California Edison [53], an investor owned utility serving 15 million people in Southern California to calculate costs. This program has an off-peak price that applies to hours outside of 5–8 pm, and an on-peak price during 5–8 pm that is twice as high. This ratio is used for illustrative purposes in these sections, but section 5.1 explores the impact of different on-peak to off-peak ratios to better reflect the various TOU programs offered by different California electricity providers. Hourly residential electricity cost for cooling is reported in terms of a monthly value by dividing the total summed hourly cost by the number of months in the simulation period to be more easily interpretable for individuals who pay monthly electricity bills.

By comparing the results for each precooling schedule, we can find the best schedule for reducing a specific variable of interest for each home design and climate zone combination, and examine trade-offs when maximizing reductions in different variables. In the remainder of this paper, we analyze the potential for reductions in peak period electricity use and reductions in CO_2 emissions while using the residential electricity cost metric to confirm that these benefits can be delivered without economic penalties to residents.

4. Results

For all four single-family homes and 16 California climate zones, the results of our simulations show that precooling with an offset temperature can achieve significant reductions in both peak period electricity demand and total CO_2 emissions relative to a constant setpoint cooling schedule. Additionally, precooling can also substantially reduce residential electricity costs given typical TOU rate structures offered in the state of California [53–56].

Our results suggest that precooling is capable of eliminating 8%–61% of peak period electricity demand for Building 1 (low AC efficiency and insulation) and 18%–82% for Building 4 (high AC efficiency and insulation) depending on the climate zone. Reductions in CO_2 emissions fell in the range of 1%–22% for the Building 1 and 2%–19% for the Building 4. While the home designs evaluated demonstrated a similar range of percent reductions for both variables across precooling schedules, the homes with inferior insulation and lower AC efficiency had much larger initial electricity consumption, and hence, much larger net absolute reductions in CO_2 and peak period electricity consumption.

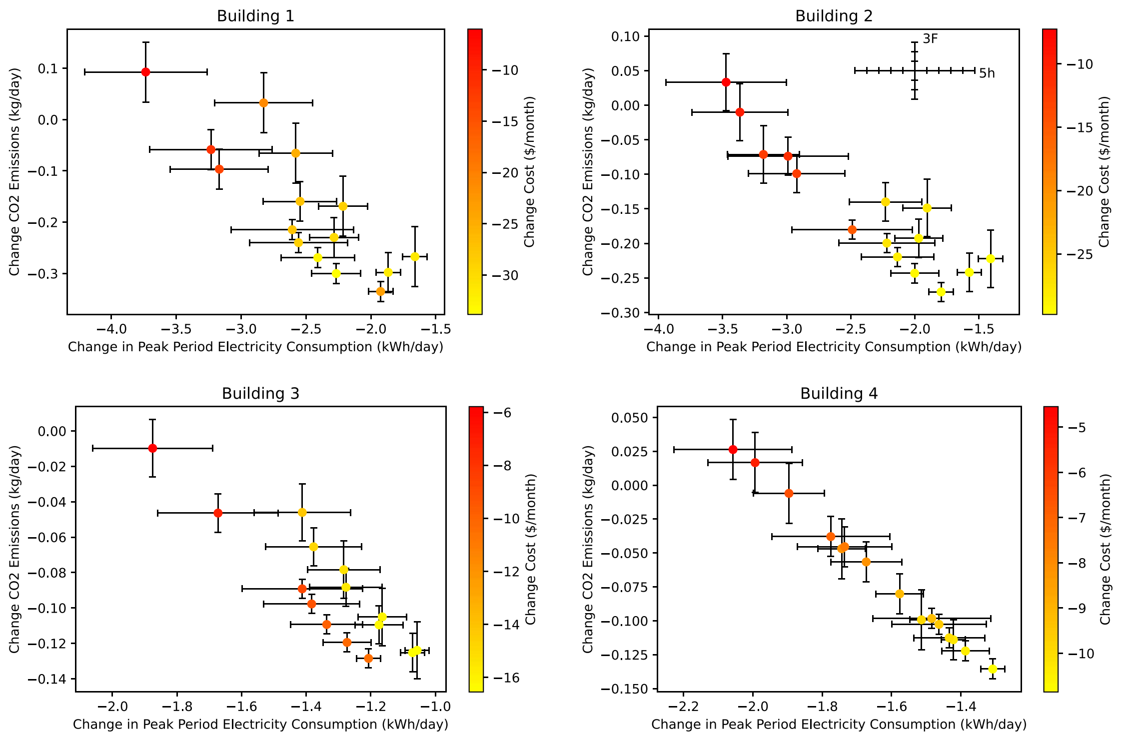

Figure 3. Changes in daily cooling related CO_2 emissions, daily kWh of electricity consumed for cooling, and monthly cooling costs over the three-month analysis period for multiple single-family home designs in California Climate Zone 9. Each point represents the precooling schedule that achieved maximum CO_2 emissions reductions for a given precooling length-depth combination, with the length and depth of the schedule shown as the width and height of the cross-hairs.

4.1. The impact of precooling schedule parameters

We first examine the impact of a precooling schedule on CO_2 emissions and residential electricity costs for a specific climate zone. In figure 3 we plot the changes in CO_2 emissions, peak period consumption, and residential electricity cost (assuming SCE's TOU rate plan) associated with a specific precooling length-depth combination for all four homes using Climate Zone 9 as an example. Climate Zone 9 is a region that includes the highly populated downtown Los Angeles and is characterized by having moderately hot summers.

Figure 3 includes one point for the simulation that most reduces CO_2 emissions for each precooling length-depth combination. Thus, each point might vary in terms of offset temperature, start-time, and reset method (see table 2 for definitions) to achieve maximum emissions reductions for a given length-depth pair. For each selected schedule, the length and depth of the precooling schedule is shown as the length and height of the cross-hairs on the associated point.

In Climate Zone 9, all home designs were able to reduce target variables significantly, with an impact of -1 to $-4\,\text{kWh}\,\text{d}^{-1}$ for peak period electricity consumption, and $+0.2$ to $-0.3\,\text{kgCO}_2\,\text{d}^{-1}$ for CO_2 emissions, depending on the home and precooling schedule (see figure 3). For all home designs, it is possible to reduce both peak period consumption and emissions simultaneously, although maximizing reductions for one variable generally reduces the reduction in the other target variable. Deeper precools (i.e. AC setpoint far below baseline during the precooling period), and to a lesser extent, longer precools, result in greater reductions in peak period electricity consumption but significantly reduce reductions in CO_2 due to the large increases in electricity consumption needed to reach the precooling temperature in the middle of the day. For these schedules, the additional CO_2 emissions during the precooling period are similar in magnitude to the avoided emissions during the offset period, meaning that even deep precools that increase overall daily electricity use for cooling can do so without increasing emissions due to the decoupling between electricity usage and grid-related emissions during hours with high VRE penetrations. On the other hand, shallow precools (AC setpoint slightly below baseline during the precooling period) offer smaller reductions in peak period electricity consumption, but the emissions penalty during this precooling period is smaller than the benefit occurred during the offset period.

When selecting the other precooling parameters that most reduced CO_2 emissions for a given precooling length-depth combination, the offset temperature selected was always 3 °F above the baseline temperature, with higher offsets eliminated by the thermal comfort constraints. Higher offset temperature consistently leads to lower CO_2 emissions and peak period demand. The start time that most reduced CO_2 emissions

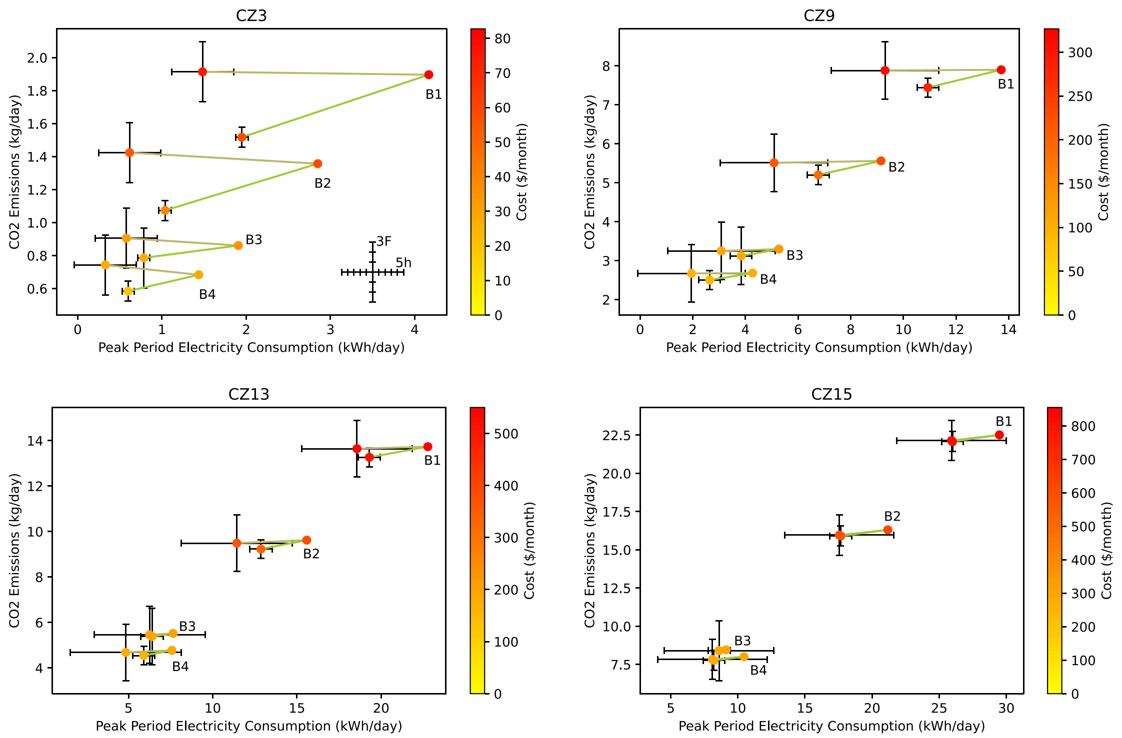

Figure 4. The emissions, peak period electricity consumption, and residential electricity costs for the baseline cooling schedule as well as the precooling schedule that maximized CO_2 reductions and the one that maximized peak period electricity reductions for each of the four single-family home designs in various California building climate zones. The length and depth of the schedule are shown as the width and height of the cross-hairs.

varied for the different precooling lengths and depths, as well as the specific home, but the vast majority of selected schedules started at 4 or 5 pm, which is the period of the day when the grid transitions from high penetrations of solar generation to large penetrations of natural gas and imports. The reset method that most reduced CO_2 emissions also depended on the home selected and precooling length and depth, with a gradual reset being the better strategy more often. The reset method had a relatively small impact on both CO_2 emissions and peak period electricity consumption.

4.2. The impact of building properties and climate zone

Next, we examine the trade-offs in precooling schedules that maximize CO_2 emissions reductions versus schedules that maximize peak period consumption reductions relative to the baseline schedule for each home within a climate zone. Figure 4 illustrates results for four distinct climate zones: Climate Zone 3 (San Francisco) representing a coastal area with mild weather, Climate Zone 9 (Downtown Los Angeles) representing a dense urban area with periodic heat waves, Climate Zone 13 (Fresno) representing an area with warm, humid summers, and Climate Zone 15 (Brawley) representing a hot, desert region.

Figure 4 shows that for all four homes across a variety of climate zones, precooling can significantly reduce peak period electricity consumption with little or no penalty in CO_2 emissions. The homes with poor insulation and lower efficiency AC are capable of larger reductions in peak period electricity consumption than those with superior insulation and higher AC efficiency due to the higher initial levels of consumption for the baseline schedule, providing larger potential for reduction. In Climate Zone 13, precooling was able to reduce peak period electricity consumption by 4.2 $kWh\,d^{-1}$ for Building 1 but just 1.2 $kWh\,d^{-1}$ for Building 4. The maximum possible reductions in CO_2 emissions are smaller in percentage than the maximum possible reductions in peak period electricity consumption, but the schedules that most reduce CO_2 emissions have the co-benefit of reducing peak period consumption significantly, especially in warmer climate zones. For example, for Building 1 in CZ15, the precooling schedule that most reduced CO_2 emissions (by 0.44 $kgCO_2\,d^{-1}$) also reduced peak period electricity consumption by 98% of the maximum possible reduction. The potential of precooling to significantly reduce peak period consumption without a CO_2 penalty, or even with a small-moderate CO_2 benefit, suggests that precooling can be used for a variety of single-family homes on a consistent basis in summer months.

We also investigate the impact that climate zone and building properties have on the effectiveness of precooling schedules by comparing the schedule that maximizes CO_2 reductions and the schedule that

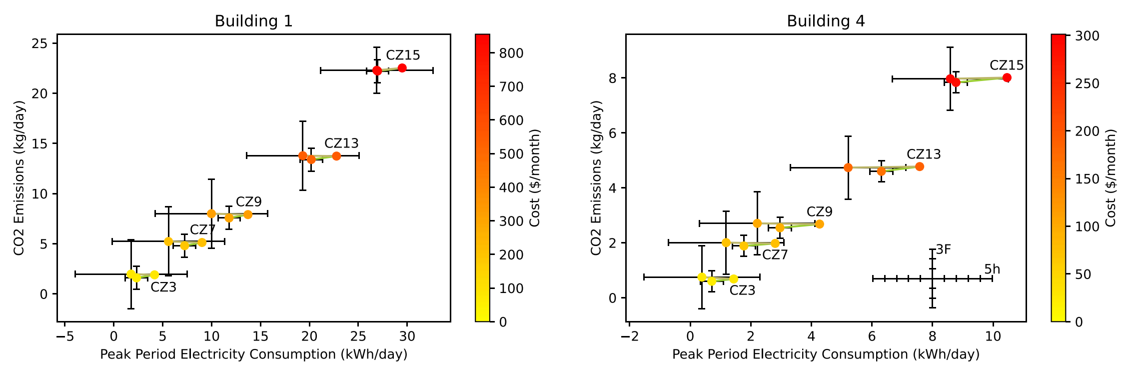

Figure 5. The emissions, peak period electricity consumption, and residential electricity costs for the baseline cooling schedule as well as the precooling schedule that maximized CO_2 reductions and the one that maximized peak period electricity reductions for Buildings 1 and 4 in five different California building climate zones. The length and depth of the schedule are shown as the width and height of the cross-hairs.

maximizes peak period reductions for each respective home across multiple climate zones. Figure 5 illustrates results for Buildings 1 and 4.

Figure 5 shows that reductions in peak period electricity consumption and CO_2 emissions from precooling are generally larger in percentage in cooler climate zones, but larger in magnitude in warmer climate zones. Warmer climate zones typically have higher baseline cooling-related electricity consumption across home designs, and thus more potential for reduction, but exact reductions in peak period electricity consumption and CO_2 emissions also depend on factors like the diurnal temperature profile (e.g. precooling tends to be more effective in climate zones where evening temperatures remain high). For these climate zones, we observe a spread of potential reductions in peak period electricity consumption ranging from 1.1 kWh d^{-1} in Climate Zone 3 to 2.4 kWh d^{-1} in Climate Zone 13 for Building 4 and 2.4 kWh d^{-1} in Climate Zone 3 to 3.7 kWh d^{-1} in Climate Zone 9 for Building 1. Similarly, daily CO2 emissions can be reduced by 0.081–0.18 $kgCO_2\ d^{-1}$ for Building 1 and 0.26–0.40 $kgCO_2\ d^{-1}$ for the Building 4, depending on climate zone.

5. Discussion

5.1. Impact of precooling on thermal comfort

More precooling prior to the offset period may offer improved thermal comfort for building occupants by reducing the average temperature during the offset period. Deeper and longer precools remove more heat from the building during precooling, which can cause uncomfortably cool temperatures during precooling, but then help to prevent the home from reaching uncomfortably high temperatures during the offset period. This may be preferred by occupants that find it easier to adapt to cool temperatures, or who would may be gone during the precooling period in the afternoon. We examine the impact of precooling on offset period comfort by finding the mean PMV during the 3 h offset period when the AC is set above the baseline temperature. Figure 6 shows the mean PMV as a function of the length and depth of the precool in Climate Zone 9 (Downtown Los Angeles) for Buildings 1 and 4 assuming a start time of 5 pm, an offset temperature of 3 °F, and reset method 1.

In figure 6, we see that comfort is improved during the offset period when deeper and longer precooling schedules are used, but the relatively small impact on mean PMV for both homes (for even the deepest and longest precooling schedules) suggest that this effect is minimal. For Building 1, the difference in mean PMV between the most and least precooling is 0.12, and the mean PMV exceeds ASHRAE's comfort standard (PMV $\leqslant +0.5$) for all precooling schedules. For Building 4, the mean PMV has a range of 0.16, and all of the precooling schedules have a mean PMV of less than $+0.5$ during the offset period and are therefore within the ASHRAE standard. These results suggest that it may be necessary to limit precooling to homes with appropriate building properties or consider co-adaptations to improve comfort for lower-performing homes.

We also note that comfort perception has been shown to depend on a variety of psychological factors, such as control of the thermal environment [57, 58]. Occupants may view precooling as reducing this control, negatively impacting their thermal comfort level. Additionally, both individual comfort levels [59] and resident occupancy levels [60] have been shown to vary significantly across users. This may create additional precooling opportunities beyond the scope of this study, such as eliminating more peak period consumption by precooling to deeper offsets for unoccupied homes, or further reducing CO_2 emissions by

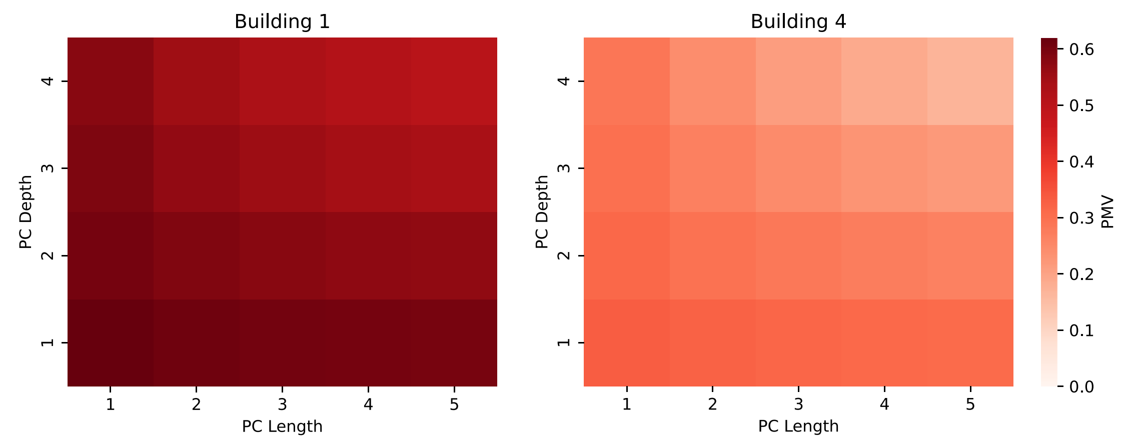

Figure 6. Mean PMV during the offset period as a function of the length and depth of the precool for Buildings 1 and 4. PMV values outside the range of −0.5 to +0.5 are considered uncomfortable; all values for Building 1 fall above +0.5 and all for Building 4 fall between 0 and +0.5.

raising the offset for users who are comfortable at higher temperatures. On the other hand, precooling may not be an appropriate strategy for potentially sensitive occupants, like young children, the elderly, or those with serious health conditions.

5.2. Influence of TOU rates

Precooling can offer utility customers cost benefits when used within TOU pricing structures that discourage electricity usage during the grid's peak demand hours. Many Californian electricity providers offer a selection of TOU programs, but here we focus on TOU pricing schedules designed to reduce consumption from 5 to 8 pm via an 'on-peak' price that is higher than the 'off-peak' price of electricity (e.g. see those offered by the Sacramento Municipality District (SMUD) [56], Southern California Edison (SCE) [53], and Pacific Gas and Electric (PG&E) [54]). For each home and climate zone combination, we identify the precooling schedule that maximizes reduction in peak period electricity consumption and use it to calculate a break-even ratio between on-peak price and off-peak price: the smallest ratio between on- and off-peak pricing for which the schedule that most reduces peak period electricity consumption also provides residential electricity cost benefits.

In figure 7, we see that cooler climate zones generally require a larger on-peak to off-peak price ratio to make the precooling schedule that minimized peak period electricity consumption also economically beneficial to residents. Outside of the coolest climate zones, most home and climate zone combinations have a minimum ratio significantly lower than 2:1. Utilities offer TOU programs with a variety of ratios, such as 1.37:1 for PG&E, 2:1 for SCE, 1.75:1 for SMUD, and 1.25:1 for San Diego Gas and Electric. Therefore, even precooling with goal of aggressively reducing peak demand will provide reduced residential electricity costs for many locations and single-family homes. Additionally, the schedules that most reduced CO_2 consistently provided reductions in residential electricity cost even when the TOU ratio barely exceeded 1, meaning that shallower, shorter precools can reduce residential electricity costs regardless of home design or location, provided offset temperature is maximized within comfort levels.

5.3. Precooling for CAISO's flex alert program

In recent years, CAISO has increasingly relied on the 'Flex Alerts' program to avoid rolling blackouts. The Flex Alerts notification system was developed by CAISO as a mechanism to request that electricity users voluntarily reduce their consumption during periods of high demand [61]. In September 2022, a Flex Alert sent via text was estimated to have reduced demand by over 1 GW in a span of just five minutes and continued to reduce demand over several successive hours [62]. On the Flex Alert website, CAISO recommends a variety of strategies for shifting consumption away from a period of high demand, including aggressively cooling your home beforehand and then avoiding cooling use during the Flex Alert period (precooling) [61]. Although CAISO recommends an AC setpoint of 78 °F or higher during the Flex Alert period, it does not offer a recommendation for a specific precooling temperature prior to the Flex Alert period. Our results suggest that precooling should be done for several hours leading up to the Flex Alert period with an AC setpoint 3 °F or more below the residents typical baseline temperature (depending on occupants' thermal comfort flexibility) to achieve large reductions in demand during the Flex Alert period.

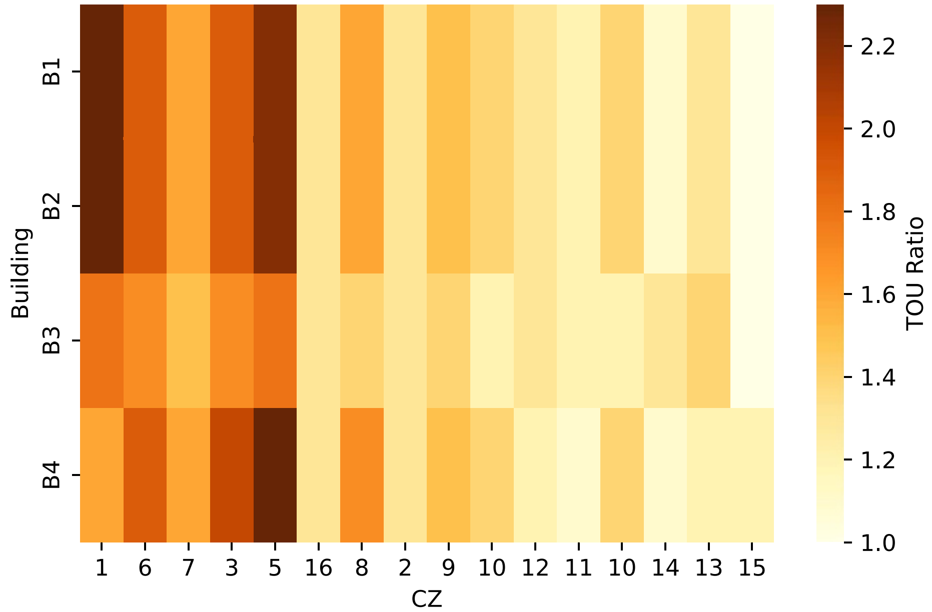

Figure 7. Minimum on-peak to off-peak electricity price ratio needed to make the the schedule that maximizes peak period electricity reductions also cost-reducing for each home and climate zone combination. Climate zones are organized by number of CDD from low to high.

Importantly, our results show that precooling can be used to by residents in single-family homes to reduce consumption during the Flex Alert period regardless of location and home insulation level.

5.4. Impact of precooling on CO_2 emissions

With CAISO's large diurnal variations in *MEF*s between mid-day and evening hours, precooling can moderately reduce cooling-related CO_2 emissions, achieving at most 20% reductions when compared to a baseline schedule, but often significantly less, as shown in section 4. Multiple factors limit precooling's effectiveness at reducing CO_2 emissions. First, the smaller thermal mass of the single-family homes considered here limits the amount of time cooling load can be shifted by. This makes it difficult to move AC usage from the highest emissions-intensity hour (often peak demand) to the lowest (often peak solar), which can occur far apart within a day. Secondly, precooling schedules take advantage of clean midday generation, which requires low AC setpoint temperatures during some of the hottest hours of the day, consuming significant additional electricity. Lastly, returning from the offset temperature to the baseline temperature causes a late-night spike in electricity consumption, a period during which the emissions intensity of CAISO is often high due to high natural gas consumption. This effect can be mitigated by a gradual reset to the baseline temperature (reset method 2), although this strategy shows mixed effectiveness depending on climate zone and selected home. Despite the modest reductions in CO_2 emissions, our results do suggest that we have the option of using precooling to aggressively reduce electricity demand during the peak period without increasing CO_2 emissions, or even with some reductions (see figures 3–5). Many schedules can reduce daily demand during the peak period by multiple kWh per single-family home while still decreasing emissions, even when total daily electricity consumption increases.

In summer months, CAISO's diurnal profile of both *AEF*s and *MEF*s (see figure 2) feature lower mid-day emissions factors and higher emissions factors in the evening. The precooling schedules discussed in this paper aim to specifically take advantage of this pattern by aligning the increased electricity caused by precooling with periods of lower emissions factors, and reducing cooling when the emissions factors are higher. For other electricity grids that are less solar-dominant, precooling 1) might not be a viable strategy for emissions reductions in these regions, or 2) might have to be scheduled during a different portion of the day that takes advantage of the local daily variations in emissions-intensity due to VRE availability (which might not be possible given a home's thermal inertia constraints). For example, for the Midcontinent Independent System Operator, *MEF*s in summer months [63] show a trend of being lower in the evening; this pattern would be difficult to take advantage of to reduce emissions because cooling needs in the evening are already lower. Generally, to gain emissions benefits (in addition to the standard peak-shaving benefits of precooling) a regional grid would have to transition from lower *MEF*s to higher *MEF*s over the span of a few hours, and for AC usage to be needed during the high *MEF* period; a pattern that may become more common as more US grids transition to higher solar generation.

6. Conclusion

For all California climate zones and home designs, the precooling schedules that maximize peak period electricity consumption are deeper and longer; however, these schedules offer only slightly greater reductions in peak period consumption than shallow precool schedules that deliver simultaneous reductions in CO_2 emissions. The schedules maximizing peak demand benefits may be preferable for DR events such as CAISO Flex Alerts, but residents can achieve similar benefits with the use of a shallow precool and offset temperature, which might be more beneficial for frequent usage due to the reduced CO_2 emissions. Furthermore, for a majority of the combinations of climate zone and homes evaluated, precooling can also reduce residential electricity costs for current TOU plans offered by local utilities, with the largest cost-savings occurring for shallower, shorter precooling schedules like those that most reduce CO_2 emissions. When precooling, the transition from the precooling period (low AC setpoint) to the offset period (high AC setpoint) should occur in line with the timing of TOU rate plans if the resident is attempting to save money, or the start of a specified high demand period (such as a broadcasted Flex Alert period) if the goal is to reduce demand during a period of grid stress. The most effective precooling schedule will depend on a homeowner's goal (i.e. reducing peak demand vs CO_2 emissions vs electricity costs), as well as factors such as building envelope, HVAC efficiency, and location, With this in mind, residents of single-family buildings would benefit from utility-specific guidance on precooling or the use of optimization technology via smart thermostats. Full results for all precooling simulations (481 schedules $\times$ 16 climate zones $\times$ 4 single-family homes) can be found in the data repository online (https://data.mendeley.com/datasets/333jfmpvb8/1).

Despite the variety of homes included in this study, many specific building characteristics remain untested, such as the impact of residential building size and type of AC. Large residential homes are not included in this analysis, and while more rare, they may contribute significantly to residential electricity demand, and associated CO_2 emissions, due to their large daily consumption. This study also focused on homes with central AC, and the impact of precooling on homes with individual window or wall AC units was beyond the scope of this study. While the homes included in this study were selected to be reflective of many single-family homes in California, apartment and multi-family buildings in the residential sector were not considered. For the prototypes used in these simulations, we did not analyze their relative frequency in the existing building stock, and scaling individual building results to grid-level impacts is beyond the scope of this study.

While the results of this study show that precooling can reduce CO_2 emissions on a daily basis, a permanent or season-long shift to precooling may reduce the applicability of MEFs, and create a scenario where AEFs should be considered when calculating emissions. The similar diurnal patterns of AEFs may create the same co-benefits of precooling, but this has only been studied for a single home design in California [30]. All precooling schedules require some flexibility on thermal comfort, and the comfort sensitivity of occupants may limit precooling's ability to reduce the target variables. Precooling can sometimes create uncomfortably cool conditions (for precools with large depth), and thus rely on occupants either having programmable thermostats and being away from the home, or briefly adapting to a cooler environment (such as through the use of additional clothing). Lastly, local utilities offer a variety of TOU rate plans, and precooling should be done strategically with a specific TOU plan in mind if the goal is to reduce residential electricity cost; in general, if the goal is cost reduction, precooling is best used leading up to the period during which there is an elevated per kWh price for residential electricity, with offset used to the limit of the occupants comfort during the following higher price period.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://data.mendeley.com/datasets/333jfmpvb8/1.

Table A.1. Key properties of selected resstock buildings [32].

Building	Ceiling R-Value	Wall R-Value	AC Efficiency
Building 1 (B1)	R-13	None	SEER 10
Building 2 (B2)	R-19	R-11	SEER 13
Building 3 (B3)	R-30	R-15	SEER 10
Building 4 (B4)	R-49	R-19	SEER 13

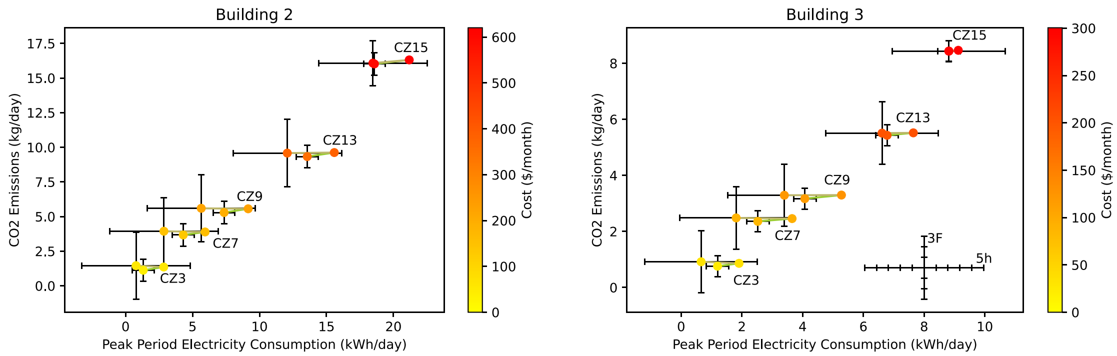

Figure A.1. The emissions, peak period electricity consumption, and residential electricity costs for the baseline cooling schedule as well as the precooling schedule that maximized CO_2 reductions and the one that maximized peak period electricity reductions for Buildings 2 and 3 in five different California building climate zones. The length and depth of the schedule are shown as the width and height of the cross-hairs.

Appendix. Supplemental information

A.1. Building properties

The four single-family homes simulated feature a range of window and wall insulation levels as well as AC efficiencies. Higher R-values indicate better insulation, and higher SEER rating indicates a more efficient AC system.

A.2. *MEF* and *AEF* calculations

As mentioned in section 3.6, the calculation of *AEF*s and s is performed following the methodology of Zohrabian *et al* [4] and is described in brief here.

*AEF*s were calculated by grouping the 2021 data by month and year (288 groups), and then regressing hourly emissions on hourly demand for electricity (with an intercept term). This resulted in 288 unique *AEF*s, with all hours of the same month sharing the same *AEF*.

*MEF*s were calculated by by grouping the 2021 data by month and demand level (ten unique demand levels), and regressing hour-to-hour changes in emissions on changes in demand and supply of variable renewable energy (and an intercept term). The coefficient of the demand term is taken as the *MEF* for that hour and demand level combination, and the results were then converted to the month-hourly level (to match the *AEF*s) by taking a probability-weighted sum; the *MEF* for a month-hour depended on the likelihood that an hour would fall in a demand bin and the *MEF* associated with that demand bin.

Refer to the cited paper for more extensive explanation of the *AEF* and *MEF* calculation process, as well as to the data repository (https://data.mendeley.com/datasets/333jfmpvb8/1) for the hourly data used to calculate these *AEF*s and *MEF*s.

A.3. Additional results: the impact of building properties and climate zone

We expand on the results from section 4.2 by including results for additional climate zones and building types.

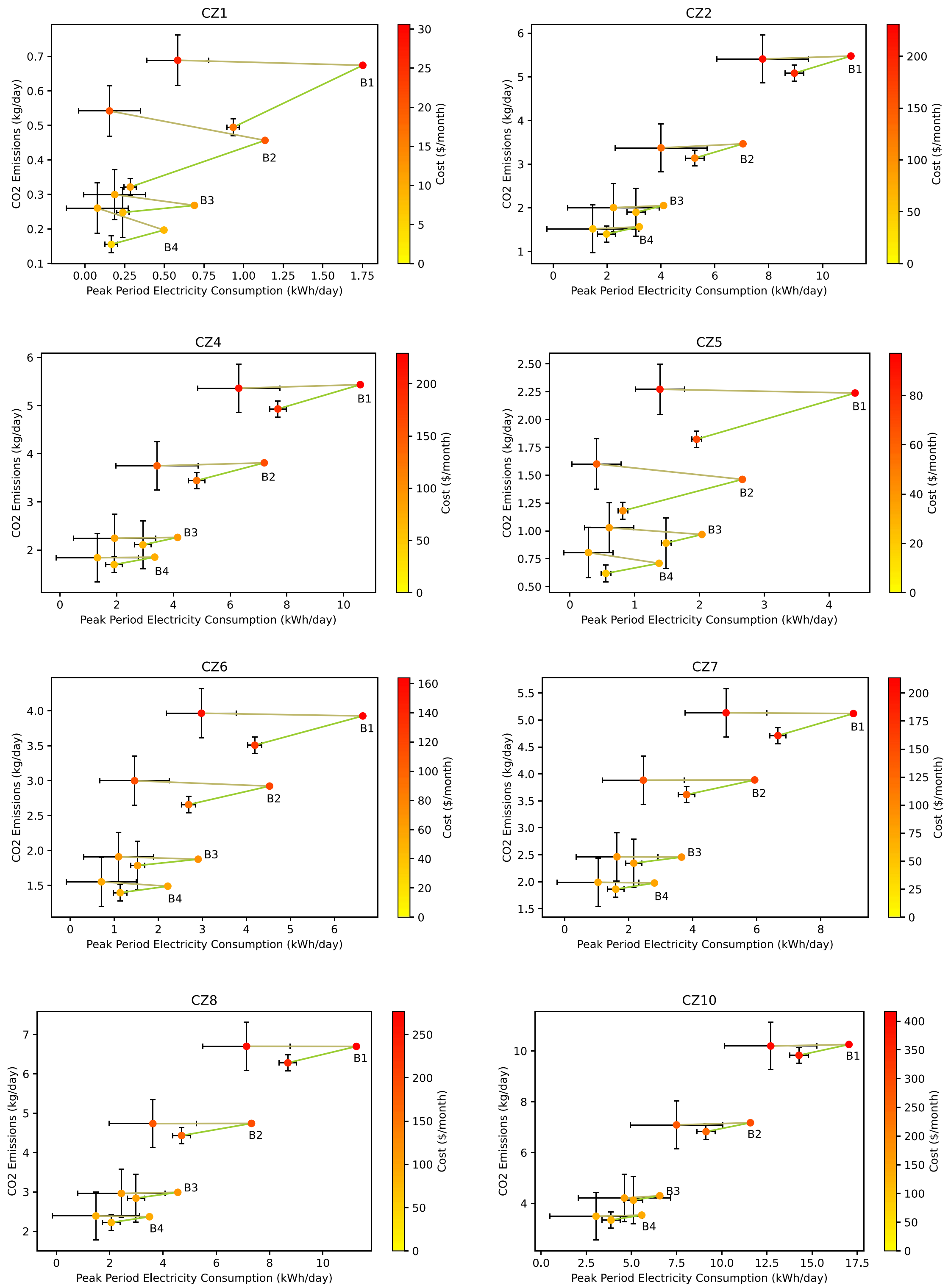

Figure A.2. The emissions, peak period electricity consumption, and residential electricity costs for the baseline cooling schedule as well as the precooling schedule that maximized CO_2 reductions and the one that maximized peak period electricity reductions for each of the four single-family home designs in various California building climate zones. The length and depth of the schedule are shown as the width and height of the cross-hairs.

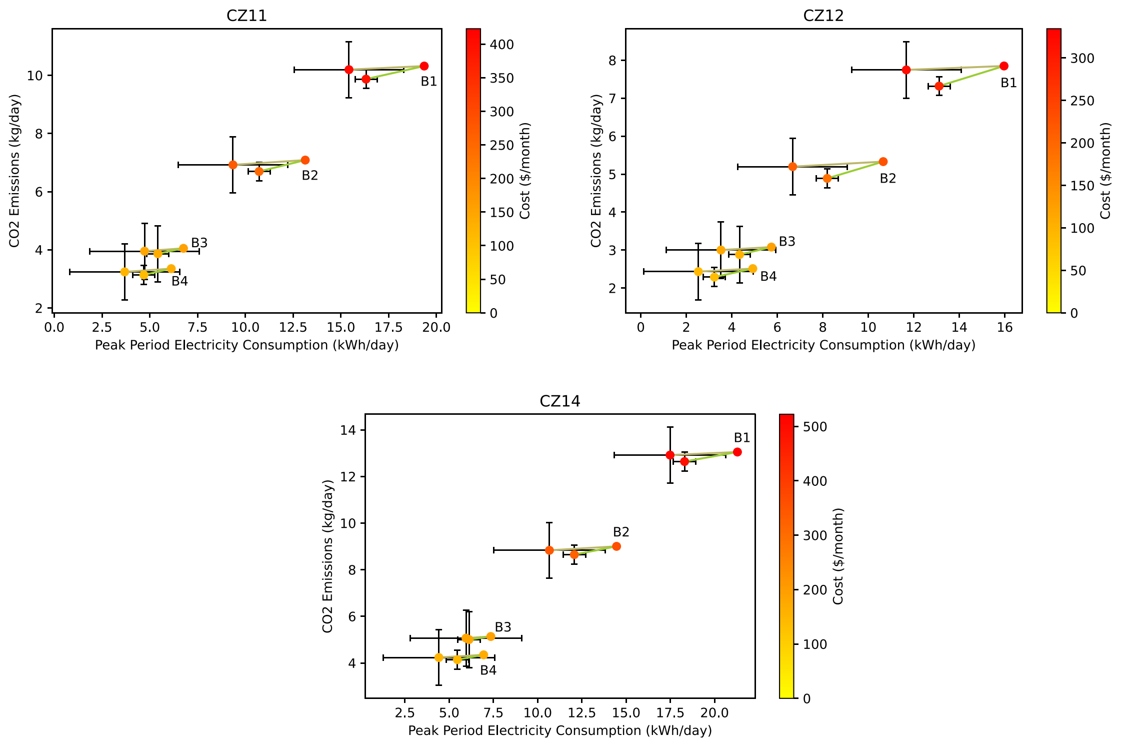

Figure A.2. (Continued.)

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