ORNL/TM-2024/3494

Design and Control of Thermal Storage for Ventilative Cooling in Multifamily Buildings

Jyothis Anand
Mini Malhotra
Piljae Im
Jonathan Woolley

July 2024

CRADA Final Report
NFE-22-09373

DOCUMENT AVAILABILITY

Online Access: US Department of Energy (DOE) reports produced after 1991 and a growing number of pre-1991 documents are available free via https://www.osti.gov.

The public may also search the National Technical Information Service's National Technical Reports Library (NTRL) for reports not available in digital format.

DOE and DOE contractors should contact DOE's Office of Scientific and Technical Information (OSTI) for reports not currently available in digital format:

US Department of Energy
Office of Scientific and Technical Information
PO Box 62
Oak Ridge, TN 37831-0062
Telephone: (865) 576-8401
Fax: (865) 576-5728
Email: reports@osti.gov
Website: www.osti.gov

ORNL/TM-2024/3494

Buildings and Transportation Science Division

DESIGN AND CONTROL OF THERMAL STORAGE FOR VENTILATIVE COOLING IN MULTIFAMILY BUILDINGS

Jyothis Anand
Mini Malhotra
Piljae Im
Jonathan Woolley

July 2024

Prepared by
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, TN 37831
managed by
UT-BATTELLE LLC
for the
US DEPARTMENT OF ENERGY
under contract DE-AC05-00OR22725

CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

Background

The concept of thermal energy storage aided natural ventilation is twofold: to provide a heat sink for cooling a building during occupancy periods at night and to improve indoor thermal comfort during the daytime with or without a minimal need for mechanical cooling. Natural ventilation through a window and mechanical circulation of the air through ventilation ducts are two key methods used to achieve night ventilation. Owing to the increasing electric need for space heating and cooling, renewable energies combined with energy storage systems are currently receiving worldwide attention. When designed and controlled properly, this strategy can reduce energy use required for cooling, the size of mechanical cooling equipment, and peak electrical demand for cooling as well as better enable demand flexibility for mechanical cooling equipment. In some cases, ventilative cooling can eliminate the need for mechanical cooling altogether. For these reasons, California's Building Energy Efficiency Standards have recently added prescriptive requirements that all new single-family residences in most California climates must include ventilative cooling systems (aka "whole-house fans"). However, these current standards do not address multifamily buildings because market-available ventilative cooling products are designed for single-family residences and are physically incompatible with many multifamily building archetypes due to the lack of attic spaces.

Purpose

The benefits of nighttime ventilative cooling in multifamily buildings are not well understood in the US; therefore, the current work will provide critical insights into this technology's potential. The project will investigate various methods to increase the effectiveness of current thermal energy storage (TES) technologies to store nocturnal cold air to reduce daytime mechanical cooling requirements. The scope of the study includes identifying climate zones that benefit from nighttime ventilation, ventilation TES systems, and methods to implement such systems in existing buildings. The study uses EnergyPlus whole-building energy modeling for the analysis. The study will display the potential of nighttime ventilative cooling, with the help of TES technologies, to mitigate growing energy demand in most parts of the US. The outcomes of this study will help in identifying US climate zones that can take on nighttime ventilation, thereby reducing peak load and equipment size (sometimes even avoiding system upgrades) as well as improving demand flexibility. The study also compares the benefits of nighttime cooling (e.g., a reduction in mechanical cooling energy) with the added energy associated with the increased fan usage while free cooling (i.e., ventilative precooling).

Major Findings

The results from the study show that the combination of TES on building walls and nighttime ventilation cooling can save total building energy usage by up to 9% and peak load by 16% in moderate climate zones. Controlled nighttime ventilation cooling—activating ventilation only when outdoor conditions are favorable—can also provide total electricity savings of up to 5% and 7% in hot and cold climates, respectively. In moderate climates, nighttime ventilation cooling can eliminate the need for mechanical cooling during overnight hours; this can also significantly reduce carbon emissions. The results from this work show that TES-aided nighttime ventilation can be implemented in most locations with proper control strategies; however, the magnitude of reduction in energy savings varies based on the number of days that are favorable for nighttime ventilation cooling.

1. INTRODUCTION

The increasing demand for space cooling is a challenge for the regional grid. From 1990 to 2016, space cooling energy consumption has tripled worldwide [1]. In the US, residential space cooling consumption is projected to grow from 0.9 quads in 2021 to 2.2 quads in 2050 [2]. In Canada, a previous study reported that space cooling demand will increase 15%–126% in Toronto by 2070 [3]. One option to save energy while reducing indoor thermal discomfort from heat, lowering the risk of a building overheating, and maintaining high indoor air quality is nighttime ventilation cooling [4, 5].

Several studies have investigated the role of nighttime ventilation in minimizing thermal discomfort and increasing energy savings [6, 7]. For instance, based on building energy simulations, a recent study shows that the effective use of nighttime ventilation cooling in residential buildings can yield a 47% reduction in energy consumption over the entire summer and maintain indoor air quality above required standards [8]. In the case of commercial buildings, another modeling study estimated that 9,829 kWh of energy savings were obtained over the entire cooling season with the help of nighttime ventilation cooling [9].

The benefits of nighttime ventilative cooling in US multifamily buildings are not well understood. Ventilative cooling systems (such as whole-house fans) combined with thermal energy storage (TES) are typically used in single-family buildings to take advantage of nighttime cool ambient air in moderate climate zones. Traditional ventilative cooling systems are not used in most multifamily residential buildings owing to the frequent lack of attic spaces (which are where whole-house fans are typically installed). The current study uses whole-building simulations to better understand the potential of nighttime ventilative cooling with the help of TES technologies in multifamily buildings.

2. METHODOLOGY

2.1 WHOLE-BUILDING ENERGY MODELING

This study uses EnergyPlus v9.5 to estimate the role of nighttime ventilative cooling with the help of TES technologies in multifamily buildings. EnergyPlus is an open-source platform developed by the US Department of Energy's (DOE's) Building Technologies Office as part of the building energy modeling program portfolio. This study uses DOE's prototype building models for multifamily residential buildings based on ASHRAE standard 2013 (Figure 1) of each representative city, as mentioned in Section 2.3. Table 1 shows the construction summary for the prototype building model.

The model has 36 thermal zones, of which 31 are apartment/residential units, 1 is an office unit, and 4 are apartment corridors. Apartment and office units are air-conditioned, whereas corridors are not air-conditioned. The thermal insulation for the exterior wall and roof of the multifamily prototype building model varies based on the climate zones, as instructed in 2013 ASHRAE 90.1. Lighting power density is as follows: all apartment units, 1.62 W/ft^2; office unit, 1.10 W/ft^2; and corridors, 0.54 W/ft^2. The design occupancy density is 2.63 people/1,000 ft^2 for all apartment units and 5 people/1,000 ft^2 for the office and corridors. The gross wall area of corner thermal zones (as shown in Figure 1) is 629.90 ft^2, that of non-corner conditioned thermal zones is 379.97 ft^2, and that of corridors is 110.01 ft^2. Window glass areas are 189.01 ft^2, 113.99 ft^2, and 48.11 ft^2 for corner thermal zones, non-corner conditioned thermal zones, and corridors, respectively. The corridors have an electric equipment load of 2.08 W/ft^2, and conditioned units have a load of 0.62 ft^2. Total ventilation is 27.5 cfm/person in all apartment units and 20 cfm/person in the office; no mechanical ventilation is provided for corridors. All thermal zones in the model have an infiltration flow per exterior wall area of 0.20 cfm/ft^2, and the ground corridor has infiltration (through entrances) of 1,103 cfm. Figure 2–Figure 5 show the schedules used in this study's prototype building models. The heating and cooling setpoints in the prototype building models are 70°F and 75°F, respectively. The hot water setpoint temperature schedule is always kept at 140°F.

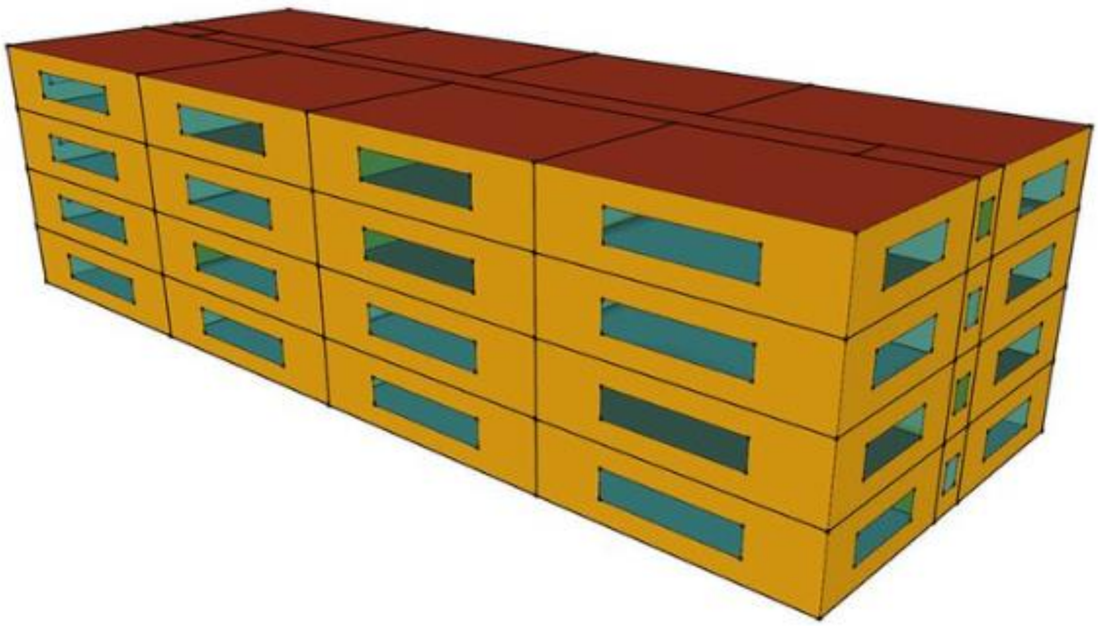


Figure 1. Multifamily prototype building model based on ASHRAE standard 2013.

Table 1. Prototype building model summary.

Exterior wall construction	Steel-frame walls (2 × 4 16IN o.c.) 0.4 in. stucco + 5/8 in. gypsum board + wall insulation + 5/8 in. gypsum board
	Nonresidential (office, corridors); residential (others)
Interior wall construction	5/8 in. gypsum board + 5/8 in. gypsum board
Roof construction	Built-up roof (roof membrane + roof insulation + metal decking)
Interior floor construction	3.94 in. normal weight concrete
Number of floors	4
Window fraction (window-to-wall ratio)	19.9%

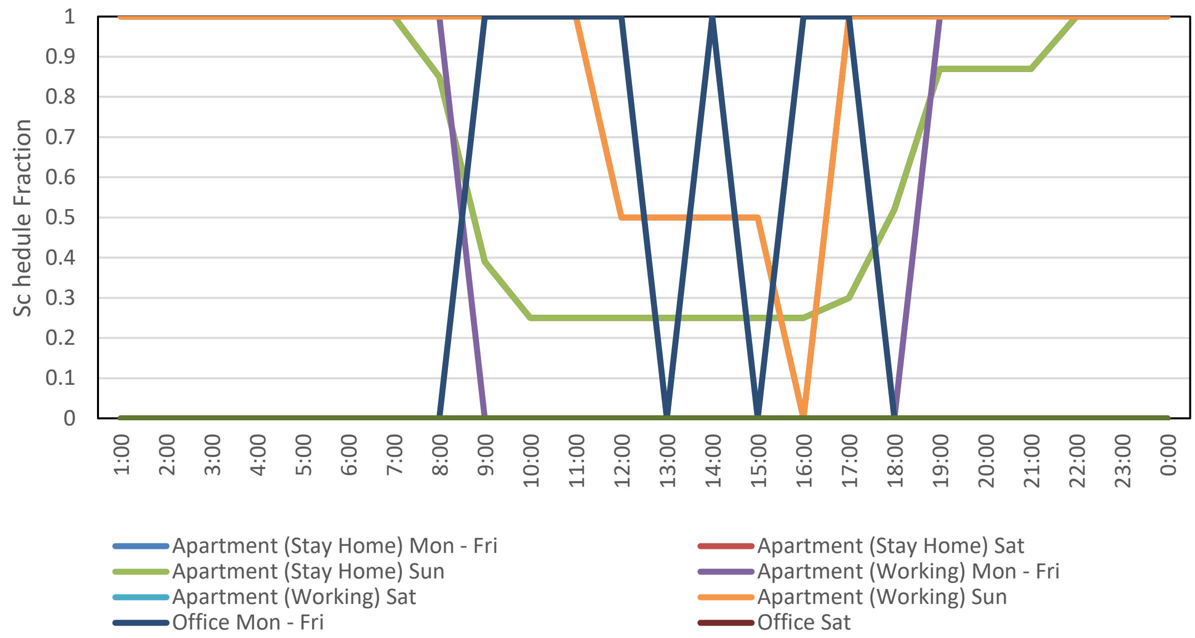


Figure 2. Occupancy schedule for all thermal zones in the building model.

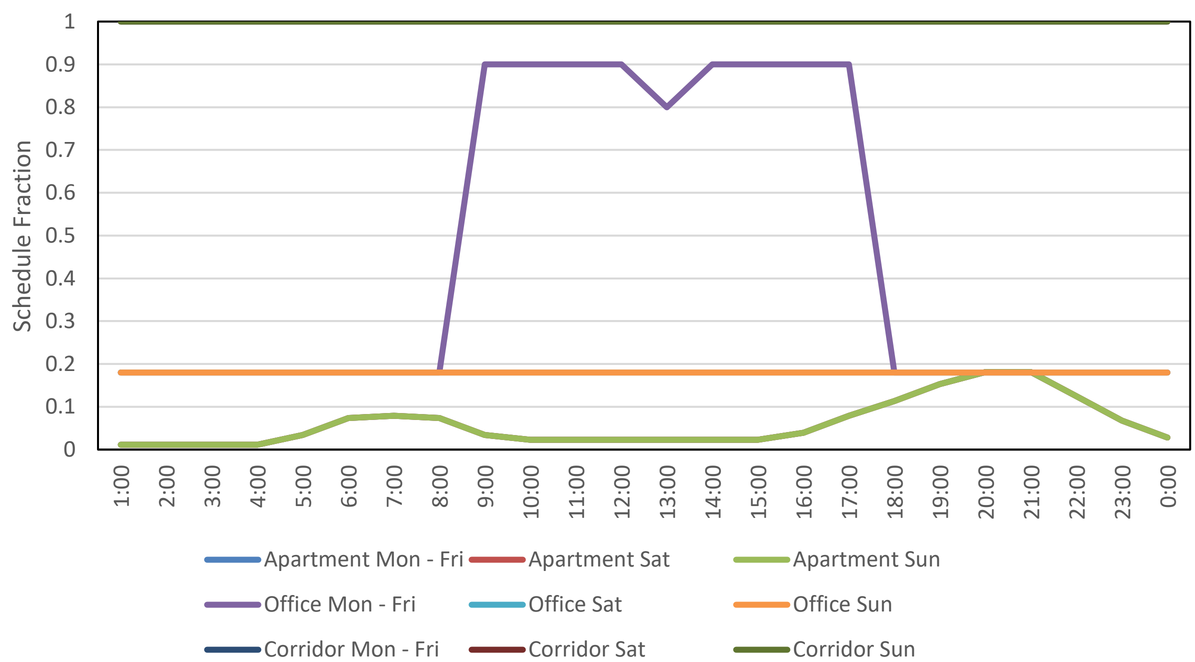


Figure 3. Lighting schedule for all thermal zones in the building model.

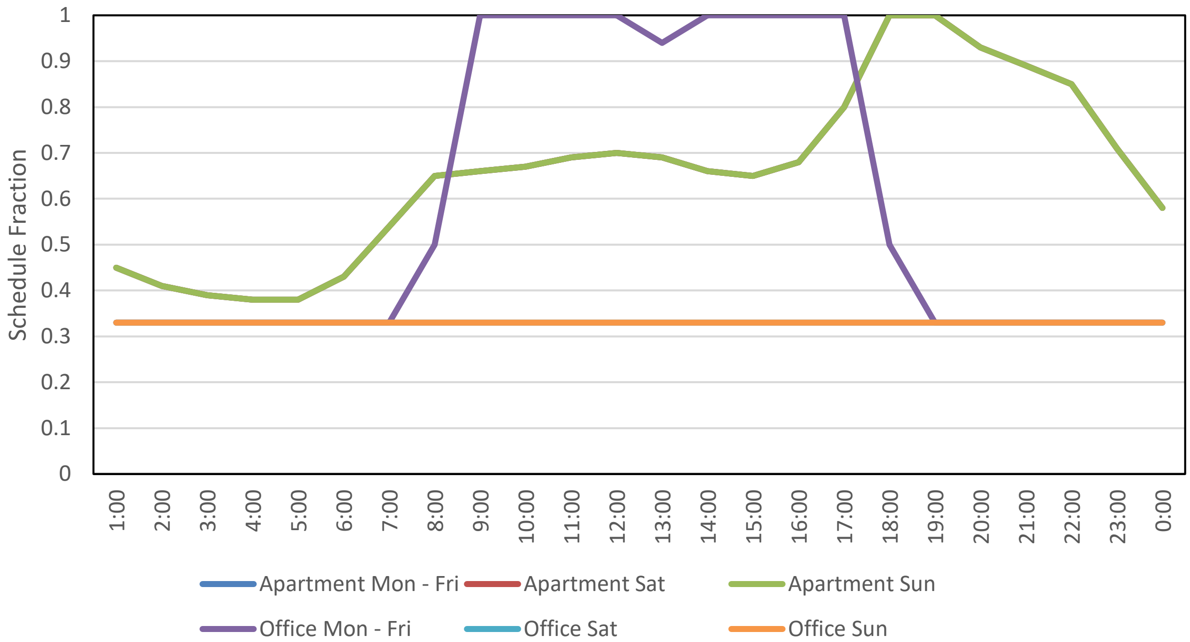


Figure 4. Electric equipment schedule for relevant thermal zones in the building model.

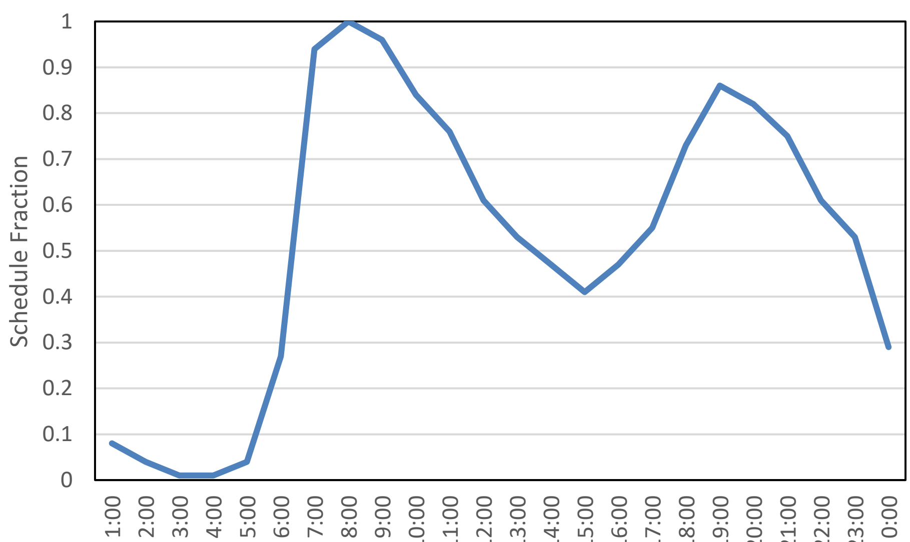


Figure 5. Domestic water heater schedule for the building model.

2.2 MODIFICATIONS IN PROTOTYPE BUILDING MODELS

The study considered the prototype building model described in Section 2.1 as the base case building for this study and considered 16 parametric simulation cases (modified based on the base case), as shown in Figure 6, to understand the benefits of combining TES and nighttime ventilation cooling. First, to increase TES capabilities of the inner surfaces, two wall and roof construction options are considered in this study: use of a 100 mm concrete layer (traditional heavy construction) for interior surfaces and use of phase change materials (PCM) on all the interior wall surfaces, as shown in Figure 7 and Figure 8, respectively. Second, to facilitate ventilation cooling in indoor spaces, three options are considered (Figure 6): kitchen exhaust fans, whole-house fans (whf), and economizers. Finally, the following three control strategies are used in this study:

1. On-off controls—Natural ventilation based on windows is scheduled between 6 p.m. and 6 a.m. This control strategy is not used in the economizer option, as shown in Figure 6.

2. Ventilation based on ΔT—Natural ventilation is based on windows scheduled between 6 p.m. and 6 a.m. only when outdoor air is favorable (i.e., when the minimum indoor air temperature is 21°C and the maximum is 0.5°C below the cooling setpoint).

3. Staged precooling—To minimize peak demand, the study considered staged precooling in combination with strategy 2's ventilation based on ΔT.

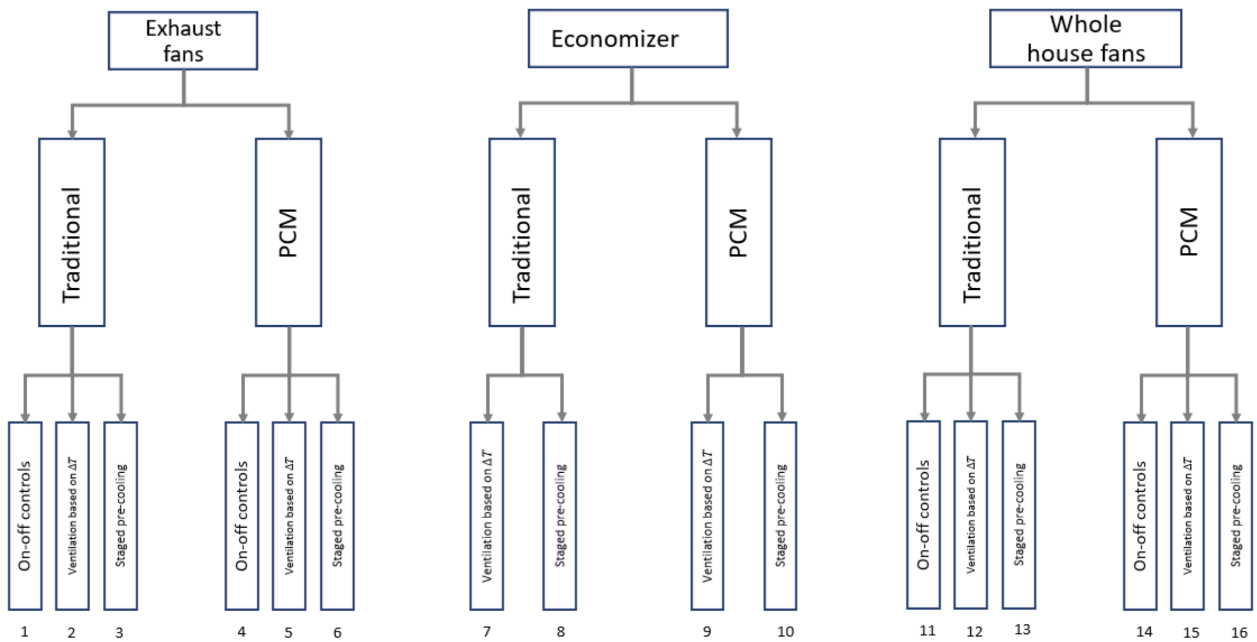


Figure 6. Flowchart used to define 16 parametric combinations for this study.

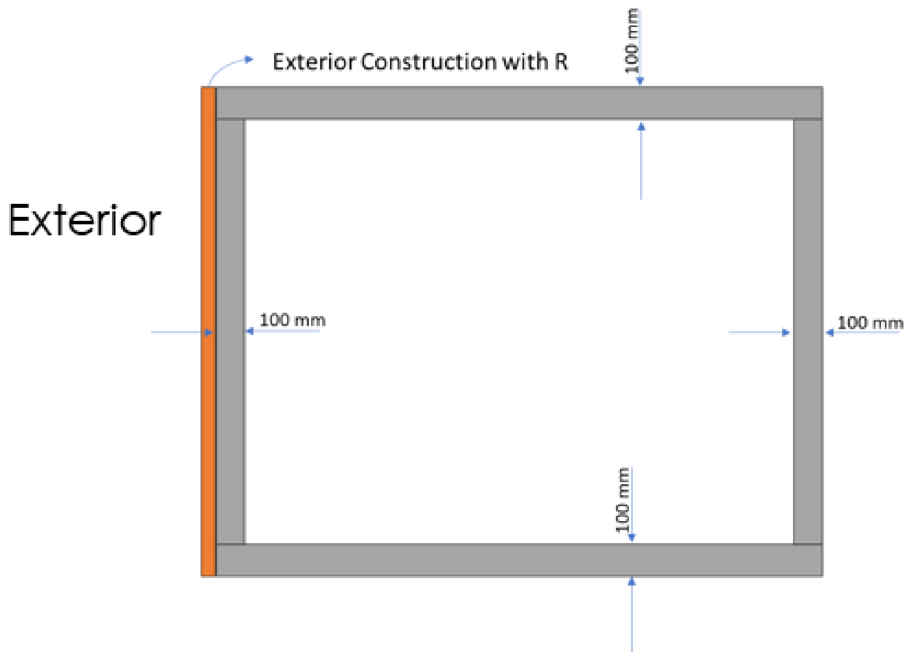


Figure 7. Concrete construction considered in this study for middle-level apartment units.

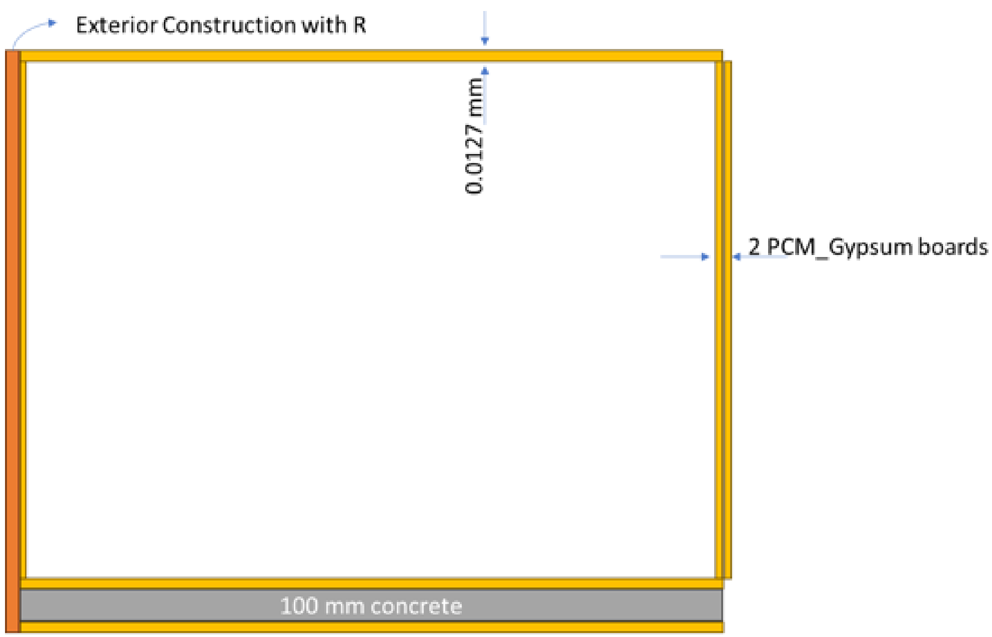


Figure 8. PCM construction considered in this study for middle-level apartment units.

The aim of this study is to understand the maximum benefits of TES on building construction. Therefore, the study used a 100 mm concrete layer for a traditional construction case, and for the PCM case, the study used 20% PCM combined with gypsum board added to all interior surfaces (e.g., floor, roof, wall; Table 2). The material properties of added/modified construction layers can be seen in Table 3; the materials already present in the prototype building model are not mentioned in the table. Because PCM is used in this study, the conduction finite difference heat algorithm, rather than the conduction transfer function (default option in prototype building model), is used in all the models in this study. In the case of the staged precooling control strategy, the study considered three cases (Figure 9) to enhance the TES capability of each apartment unit. The primary intention of these control strategies is to minimize the peak demand, especially for places like California, where the electric grid releases more carbon emissions once the sun sets (Figure 10). Therefore, the control strategies in Figure 9 show maximum peak reduction as the indoor space is precooled just before the sun sets.

Table 2. Building construction modifications used in this study.

	Traditional	PCM
Exterior wall	Interior construction layer of the reference wall (as shown in Table 1) is replaced with 100 mm thick concrete	Interior layer of the reference wall (as shown in Table 1) is replaced with 100 mm thick PCM gypsum board
Exterior roof	Interior construction layer of the reference wall (as shown in Table 1) is replaced with 100 mm thick concrete	Interior layer of the reference wall (as shown in Table 1) is replaced with 100 mm thick PCM gypsum board
Interior wall	100 mm thick normal-weight concrete	Two PCM gypsum boards
Interior floor/ceiling	100 mm thick normal-weight concrete	PCM gypsum board + 100 mm thick normal weight concrete + PCM gypsum board

Table 3. Material properties of added/modified construction layers.

	Properties	Description
Normal weight concrete	Length: 100 mm Conductivity: 2.31 W/m-K Density: 2,322 kg/m^3 Specific heat: 832 J/kg-K	The properties are based on the ASHRAE 2005 handbook
PCM-gypsum	Length: 100 mm Conductivity: 0.24 W/m-K Density: 1,271.2 kg/m^3 Specific heat: 839.52 J/kg-K Latent heat: 24,000 J/kg Melting point: 23°C ± 1°C	The study considered this construction layer to consist of 20% PCM and 80% gypsum board, as mentioned in a previous study [10]. Phase change property is implemented in EnergyPlus using “Phase Change Hysteresis” [11]. The same thermal properties are used for the solid and heating states.

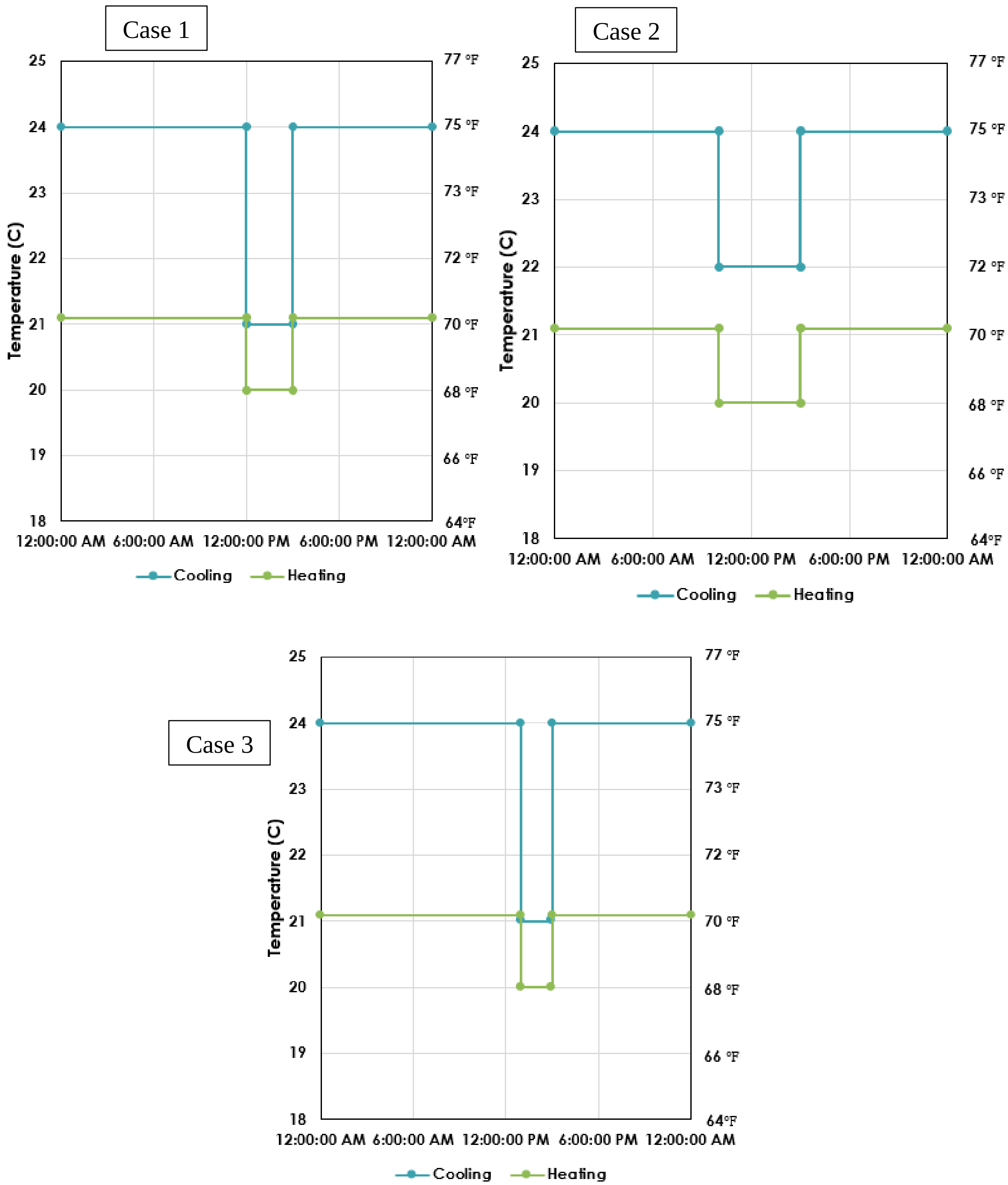


Figure 9. Three staged precooling strategies for cooling were considered in this study.

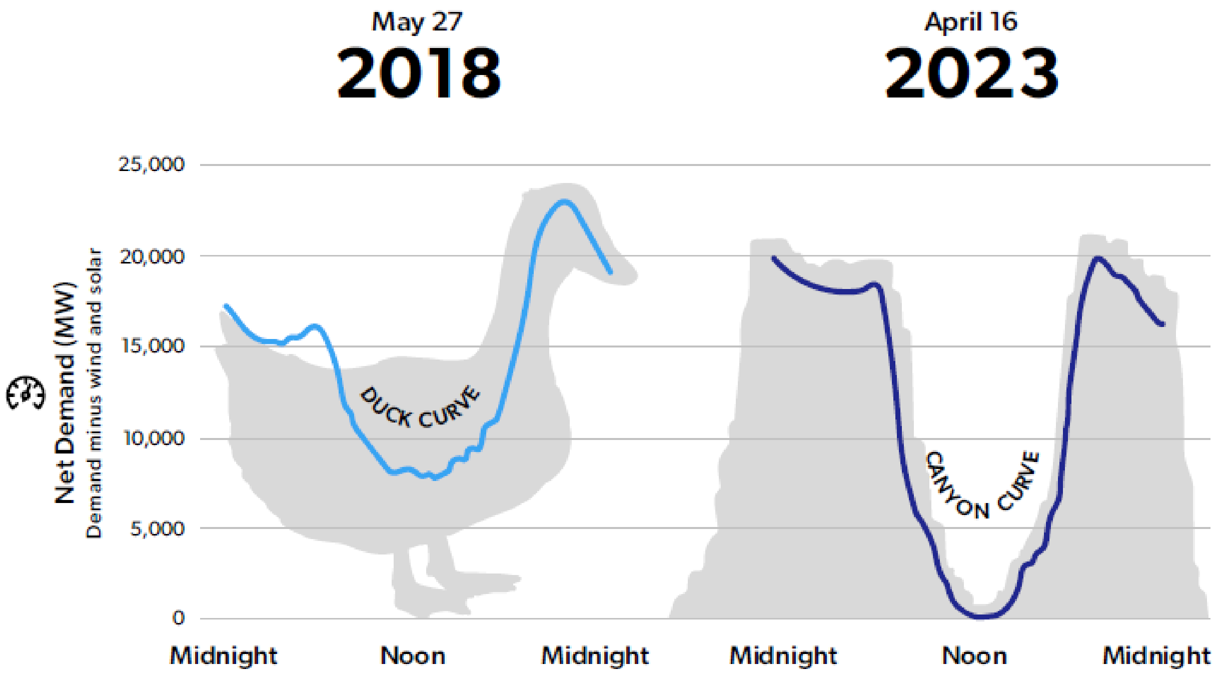


Figure 10. Grid hourly net demand metering in the state of California [12].

Two types of ventilation systems were considered in the study: kitchen exhaust fans and whole-house fans. They represent the extreme ranges of ventilation rates, with kitchen exhaust fans as a low ventilation rate option and whole-house fans representing a high infiltration rate for ventilation cooling. After considering the recommended ventilation flow rate provided by the House Ventilating Institute, ventilation rates considered for this study (per apartment unit) are 300 cfm for kitchen exhaust and 2,375 cfm for the whole-house fan. Both fan types are modeled using the design ventilation flow rate, with fan efficiency as 0.5 and ventilation type as balanced. In all the cases considered in this study, nighttime ventilation cooling is considered only between 6 p.m. and 6 a.m.; the remaining hours of natural ventilation for windows are considered based on the default setting of the 2013 ASHRAE 90.1 prototype model.

The fixed dry bulb option is selected for the economizer; the higher limit is based on ASHRAE 90.1 – 2016 standards, whereas the lower limit is kept as 10°C (50°F) because ASHRAE 90.1 does not provide a standard lower limit recommendation. Table 4 shows the ASHRAE 90.1 – 2016 standard recommendation for higher limits for the economizers in different US climate zones.

Table 4. ASHRAE 90.1 – 2016's recommended required high limits for outdoor air temperature economizer use.

ASHRAE climate zones	Required high limit (when the economizer is off)
1B, 2B, 3B, 3C, 4B, 4C, 5B, 5C, 6B, 7, 8	Outdoor air temperature > 24°C (75°F)
5A, 6A	Outdoor air temperature > 21°C (70°F)
1A, 2A. 3A, 4A	Outdoor air temperature > 18°C (65°F)

The prototype building model uses the F-factor to estimate the interaction of the building floor and ground. Unfortunately, this method could not accurately account for the thermal storage capability.

Therefore, the F-factor method was replaced with a two-layer construction. The outer layer has an effective R-value (R_{eff}) corresponding to the F-factor in each zone, estimated using Eq. 1 [13]; and the second (innermost) layer is 200 mm normal weight concrete (with thermal properties shown in Table 3). This two-layer construction is used in all models, including the reference, to maintain the same F-factor in each calculation.

$$R_{eff} = \frac{Area}{Perimeter} - 0.155 \quad (1)$$

2.3 EFFECTS OF OUTDOOR CONDITIONS

Nighttime ventilative cooling is most effective in regions where nighttime outdoor air temperatures are moderate/low enough to be advantageous but not so cool as to require heating demand. Therefore, the effect of nighttime ventilation cooling depends significantly on the location of the building. This study considers six cities—two each for representative hot, moderate, and cold regions. Table 5 lists the representative cities, and Figure 11 shows their locations.

Table 5. The representative cities from different climatic regions considered in this study.

Region types	Representative cities	ASHRAE climate zones
Hot	Houston, TX	2A
	Phoenix, AZ	2B
Moderate	Atlanta, GA	3A
	Los Angeles, CA	4B
Cold	Chicago, IL	5A
	Denver, CO	5B

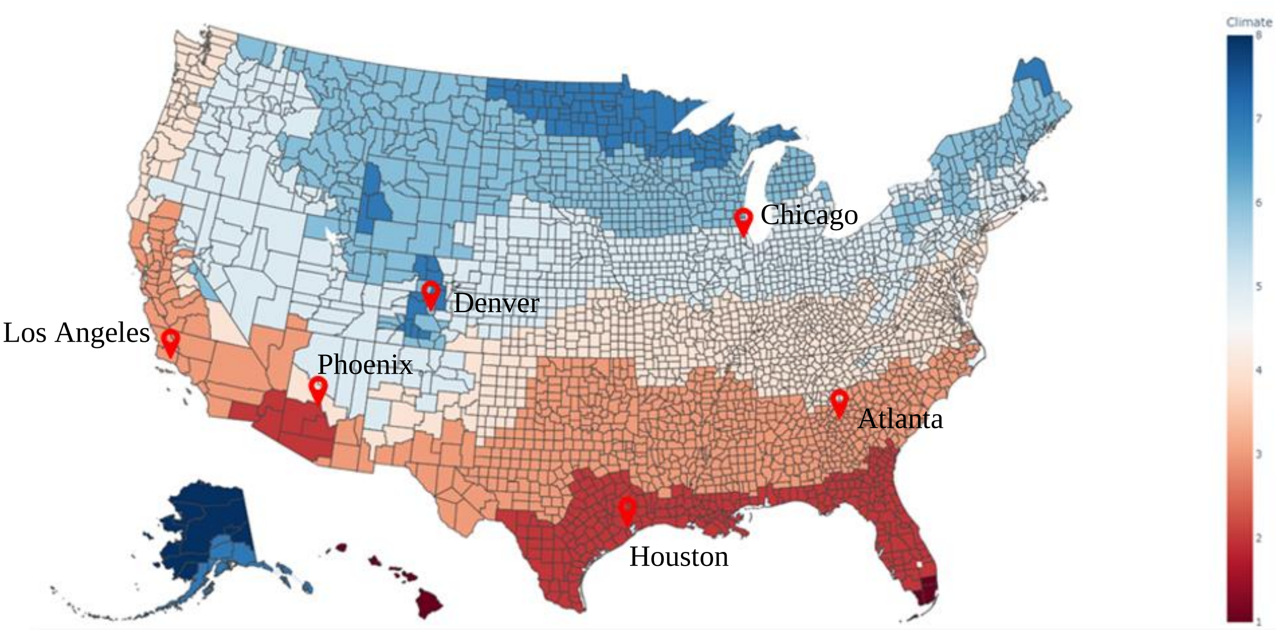


Figure 11. Location of each representative US city in this study.

3. RESULTS AND DISCUSSION

3.1 EFFECT OF VENTILATION COOLING IN LOS ANGELES

3.1.1 The Effect of Nighttime Ventilation on Whole-Building Energy Usage

Figure 12 shows the change in building energy usage for the parametric cases considered in this study, excluding the staged precooling cases. Staged precooling aims to minimize peak demand, not to reduce total energy use. The bar chart in Figure 12 shows the change in building energy usage, and the percentage value shows the percentage reduction (if the values are positive) or increase (if the values are negative) with respect to the base case. The results show that only the whf cases, which can be on constantly between 6 p.m. and 6 a.m. (simple on-off control case), show an increase in building energy usage when compared with the reference building (Figure 12). In all other cases, building energy usage is lower than that of the reference model. The maximum savings observed in whole-house fan cases with ΔT ventilation cases are 9% and 8% for traditional concrete construction and PCM construction, respectively. The results also show that uncontrolled whf use increases the electricity usage owing to the associated heating penalty. In the case of an exhaust fan, with a flow rate significantly lower than that of a whf, the heating penalty is not observed. The minimum savings (excluding two whole-house fan cases with simple on-off control cases) can be seen in the economizer cases at 4% and 3% for traditional concrete construction and PCM construction, respectively. Interestingly, the kitchen exhaust fan cases show a modest savings (Figure 12) of around 6% in all cases, which indicates the potential of TES-aided nighttime ventilation using kitchen exhaust fans in multifamily buildings.

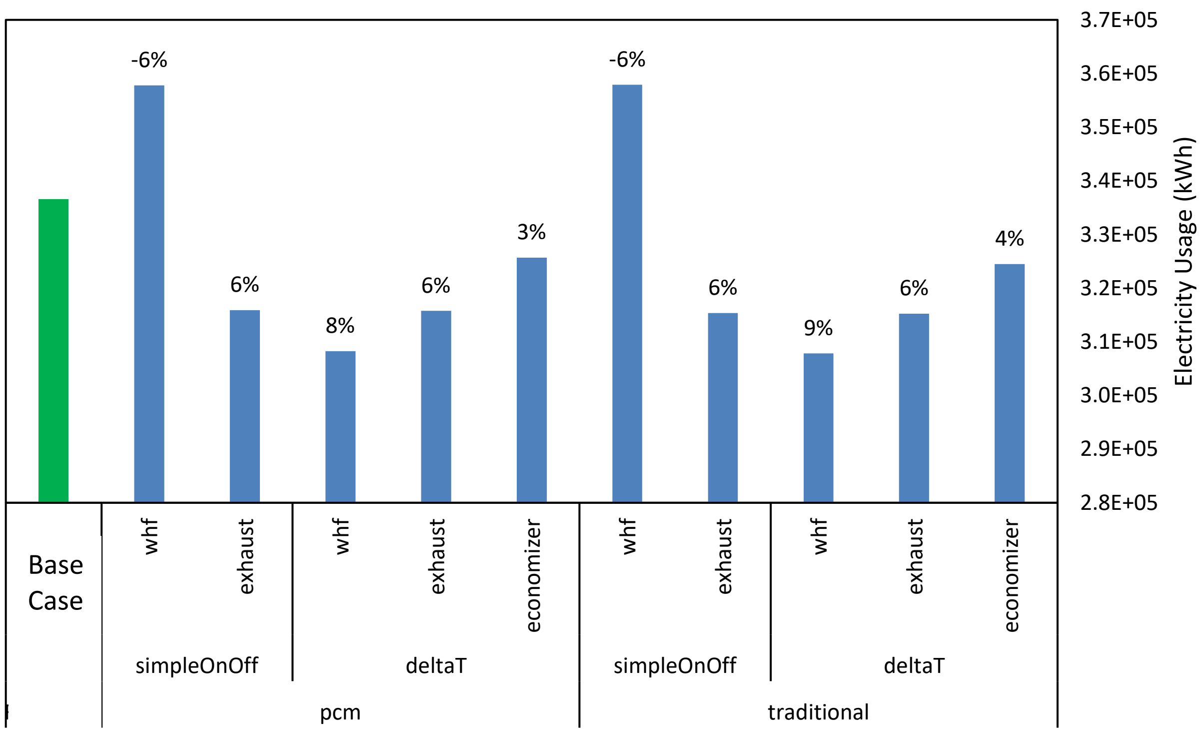


Figure 12. The changes in whole-building energy usage in the considered cases (excluding the staged precooling cases).

Figure 13 shows the change in cooling energy usage for the considered cases. Interestingly, a whole-house fan reduces the maximum reduction in cooling electricity usage, above 90% (see Figure 13), yet

Figure 12 shows a penalty in whole-house fan cases if the controlling option is simple on-off. The reason for these patterns is that uncontrolled whf (always switched on between 6 p.m. and 6 a.m.) can result in a need for space heating, thereby increasing fan usage to support heating demand/supply (Figure 14). For the uncontrolled whf cases, fan energy usage is almost doubled, thereby increasing total building electricity (Figure 12). An additional penalty in natural gas usage will result from increased space heating. Interestingly, because of the small flow rate of kitchen exhaust, additional space heating is not need, thereby not causing any penalty (Figure 14). The fan energy for the simple on-off case and ΔT ventilation case for kitchen exhaust shows no visual difference; a similar pattern can be seen in Figure 12 for total electricity usage.

Even though kitchen exhaust and whole-house fans can save cooling electricity (up to 74% and above 90%, respectively) and fan energy (up to 15% and above 30% [for the ΔT ventilation case], respectively), their impact on whole-building energy usage is less than 10% (Figure 12). This pattern is mainly due to the overall lower energy consumption for cooling and fan usage (Figure 15); only 15% of the total electricity is due to cooling and fan usage. Therefore, TES-aided nighttime ventilation cooling can reduce the total cooling energy usage (cooling + fan) by almost half.

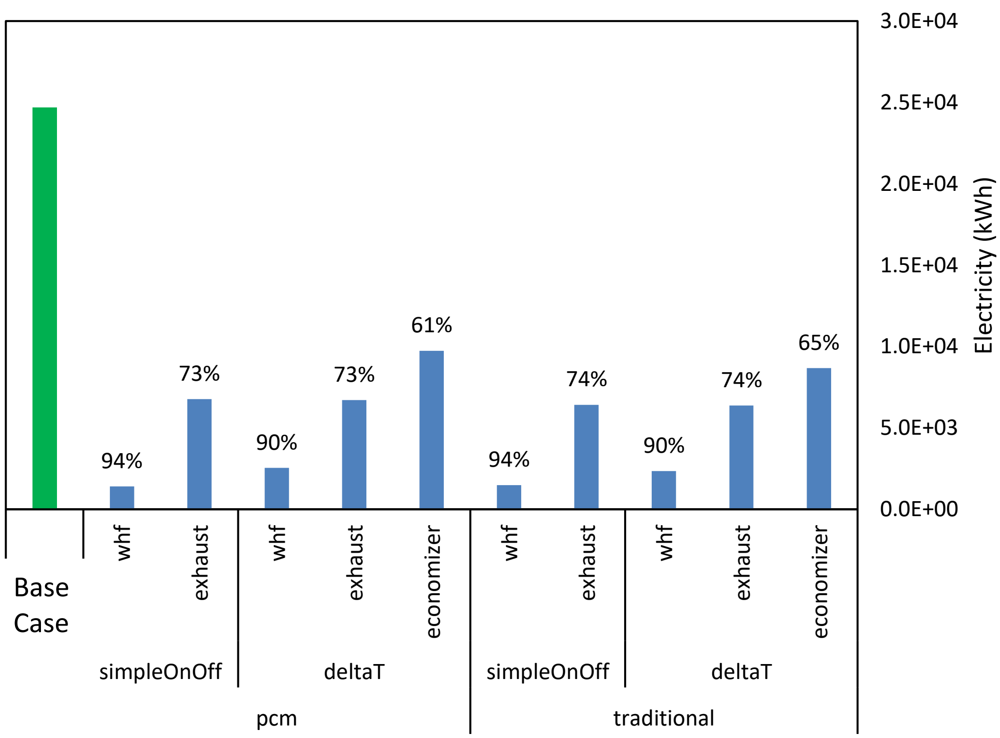


Figure 13. The change in cooling energy usage in the considered cases (excluding the staged precooling cases).

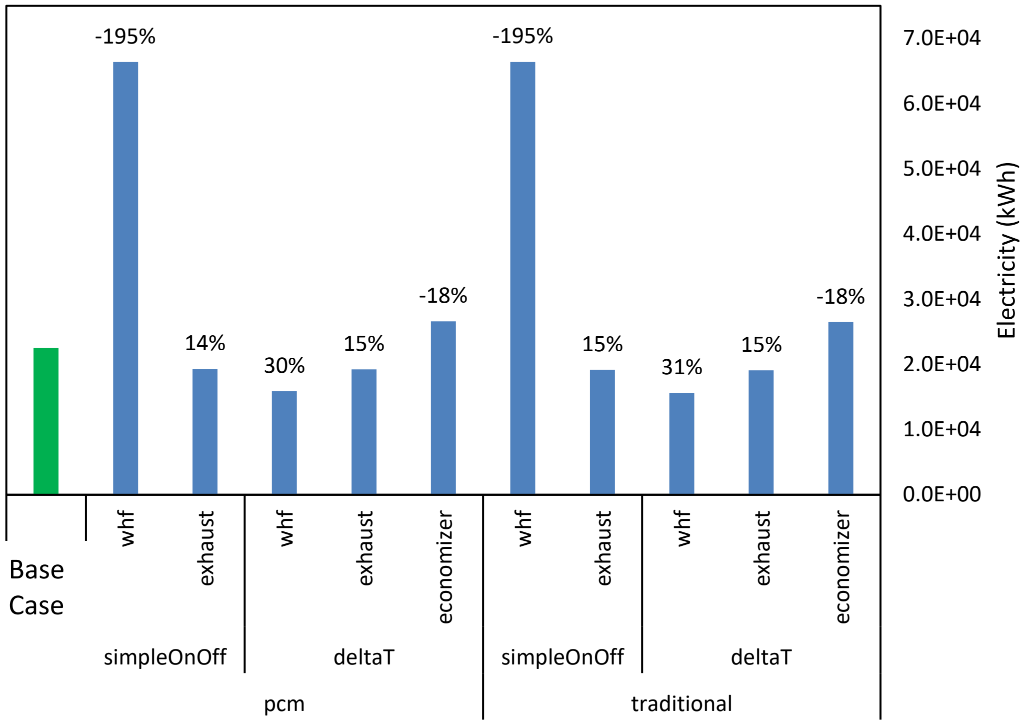


Figure 14. The change in fan energy usage in the considered cases (excluding the staged precooling cases).

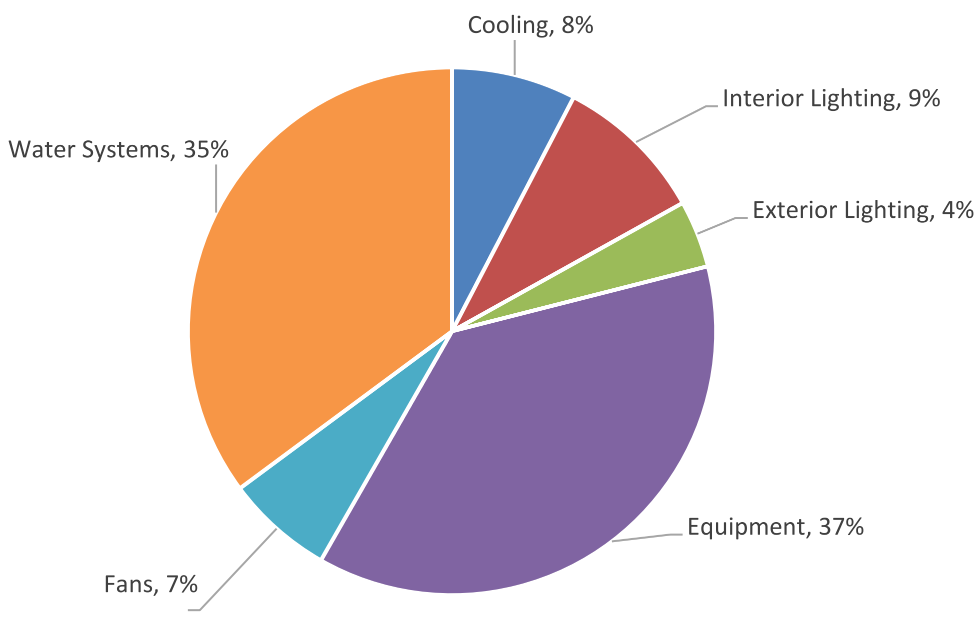


Figure 15. The distribution of energy requirements of each component in the base residential building.

3.1.2 The Effect of Staged Precooling on Peak Demand and Nighttime Energy Usage

Figure 16 and Figure 17 show the hourly energy usage for cooling and fans for hourly use with cooling needs on a hot day in Los Angeles. The results from Figure 16 and Figure 17 show that the reference case has a considerable cooling load at night, and peak cooling needs are observed after 4 p.m. for the reference case. Interestingly, even without staged precooling, the use of TES-aided nighttime ventilation can eliminate the nighttime cooling needs for moderate cities like Los Angeles. This method has the potential to further reduce carbon emissions in California, where nighttime CO_2 emissions are significantly higher than those of daytime, as shown in Figure 10 [12]. Interestingly, the TES-aided nighttime ventilation can also reduce daytime electricity usage (Figure 16 and Figure 17) owing to thermal storage at night and use during the day. This could potentially help mitigate the increase in residential electricity use associated with the work-from-home job culture [14].

Based on Figure 16 and Figure 17 , even without staged precooling, peak demand is significantly reduced owing to the nighttime TES. However, adding staged precooling can further reduce electricity demand during the desired hours, which in this case is after 4 p.m. When considering total building electricity, the research team observed an approximately 17% reduction in peak electricity demand based on July 3 weather conditions.

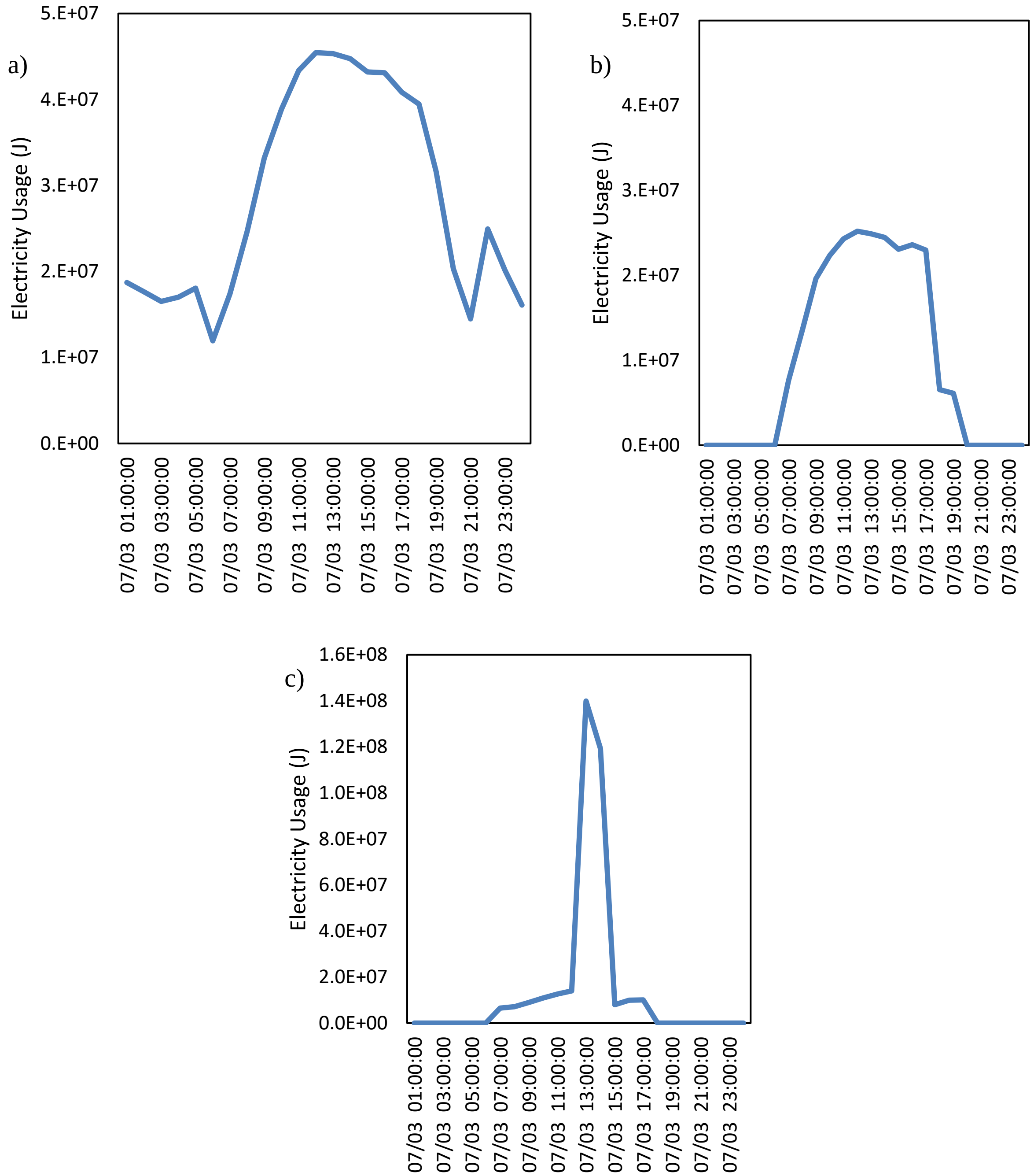


Figure 16. Hourly energy usage during a peak summer day for (a) the reference building, (b) case 2 (of Figure 6), and case 6 (with control strategy 1).

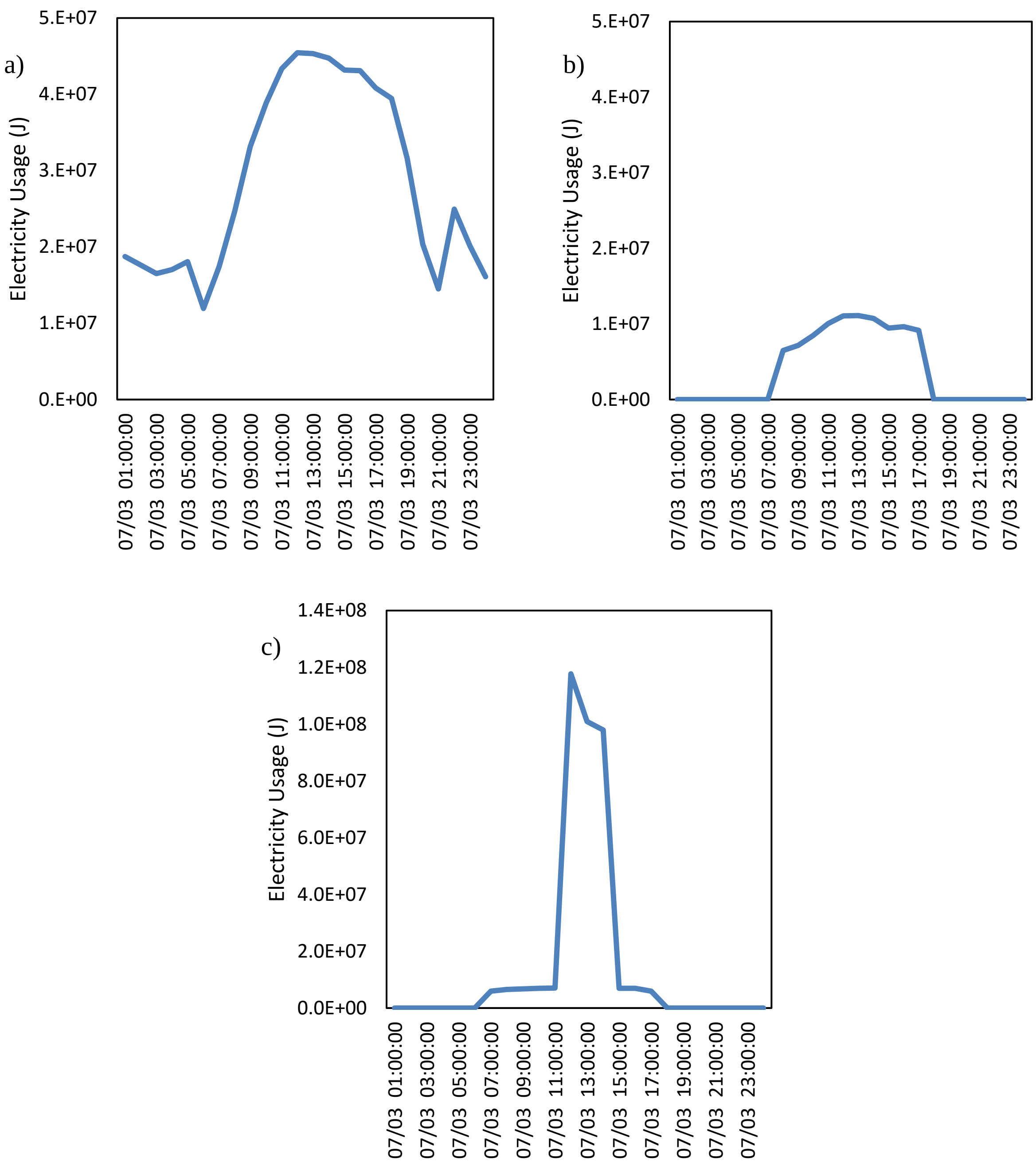


Figure 17. Hourly energy usage during a peak summer day for (a) the reference building, (b) case 2 (of Figure 6), and case 6 (with control strategy 2).

3.2 EFFECT OF VENTILATION COOLING IN ATLANTA

3.2.1 The Effect of Nighttime Ventilation on Whole-Building Energy Usage

Figure 18 shows whole-building electricity usage for Atlanta for the considered cases (excluding the staged precooling cases). The study results show that, much like with Los Angeles, simple on-off control is not a feasible solution for Atlanta owing to colder nighttime temperatures (especially in winter). Colder nighttime temperatures increase heating needs and fan energy, thereby increasing electricity needs. These maximum energy savings are for whole-house fans (for both traditional and PCM constructions). Because of the lower number of favorable hours for ventilation (for the ΔT ventilation case), the maximum saving observed are 6% and 2% for whole-house and kitchen exhaust fans, respectively. Of course, these savings occur only during the moderate months, whereas months with colder or hotter nighttime temperatures will not have active/working ventilation.

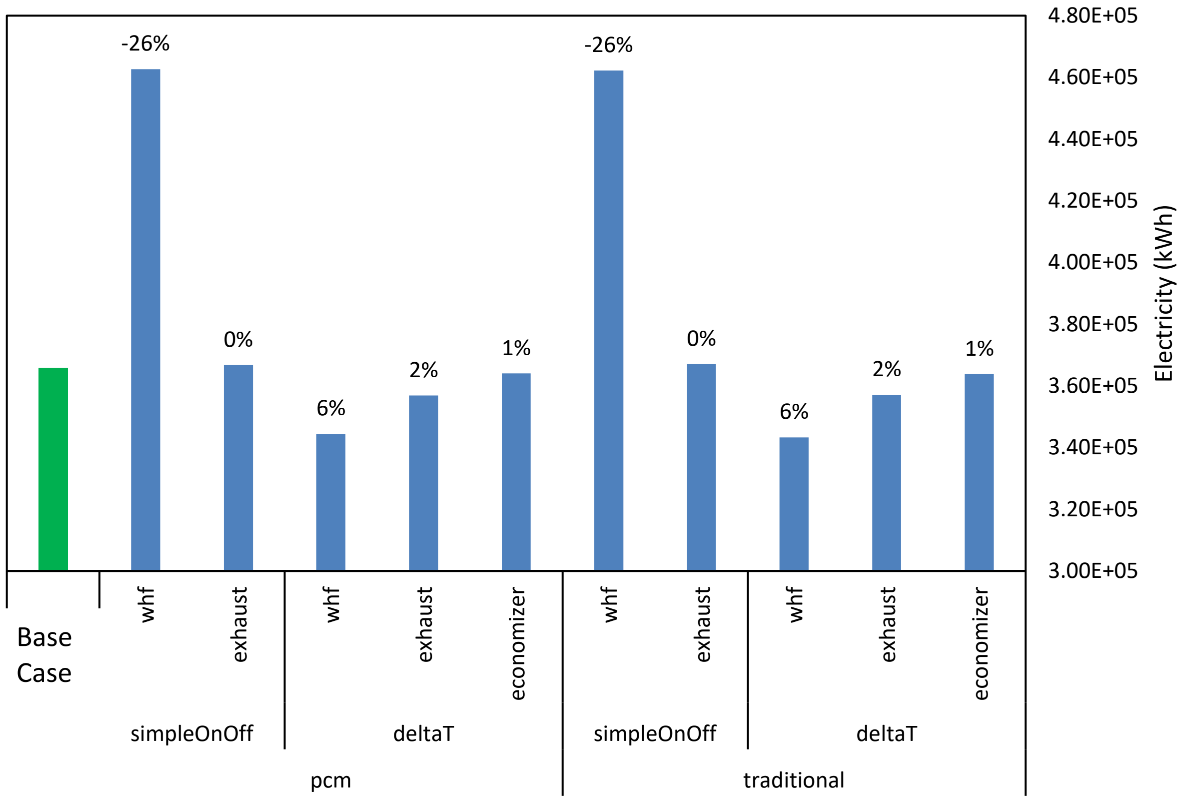


Figure 18. Whole-building electricity usage for Atlanta for the considered cases (excluding the staged precooling cases).

3.2.2 The Effect of Staged Precooling in Peak Demand

Figure 19 shows the peak reduction when implementing staged precooling on TES-aided nighttime ventilation cooling. The study results show that achieving a peak reduction as high as 14% using this technology is possible. The peak reduction is highest for the whole-house fan, owing to a higher ventilation rate; the kitchen exhaust fan offers a lower peak reduction rate, followed by the economizer with the lowest peak reduction. Overall, traditional normal-weight concrete construction has higher savings than that of PCM construction because of the higher amount of quantity (concrete) used in this study, as shown in Table 3.

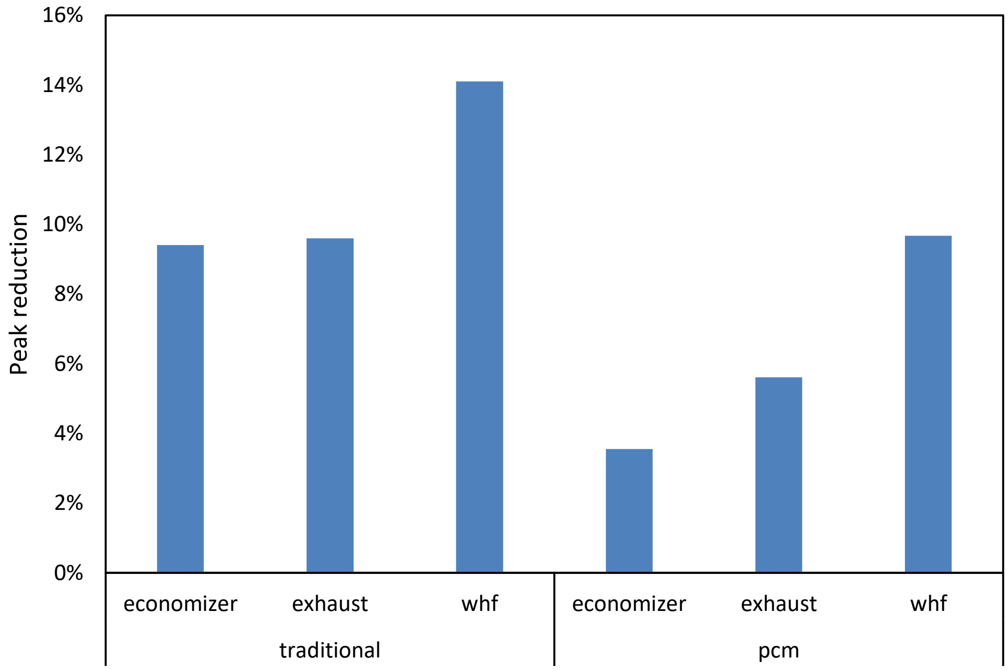


Figure 19. Peak reductions achieved while using staged precooling.

3.3 EFFECT OF VENTILATION COOLING IN HOT CITIES

3.3.1 The Effect of Nighttime Ventilation on Whole-Building Energy Usage

In hot cities, simple on-off control is not considered because nighttime temperatures are considerably higher than those of the cooling set point during most of the summer. Results for the remaining cases can be seen in Figure 20. Interestingly the hot cities' savings are somewhat similar to that of Atlanta (Figure 18 and Figure 20) because of the hot cities' milder winters. However, the overall magnitude of savings is less than half of that of Los Angeles (Figure 12). In the case of Phoenix, the maximum saving observed are 4% and 2% for whole-house and kitchen exhaust fans, respectively, for both types of construction. For Houston, the maximum saving observed are 5% and 2% for whole-house and kitchen exhaust fans, respectively, in both cases. The effect of nighttime ventilation on peak demand is considered for these cases but determined to not be viable because the nighttime temperature on peak summer days is significantly hotter than the cooling setpoints.

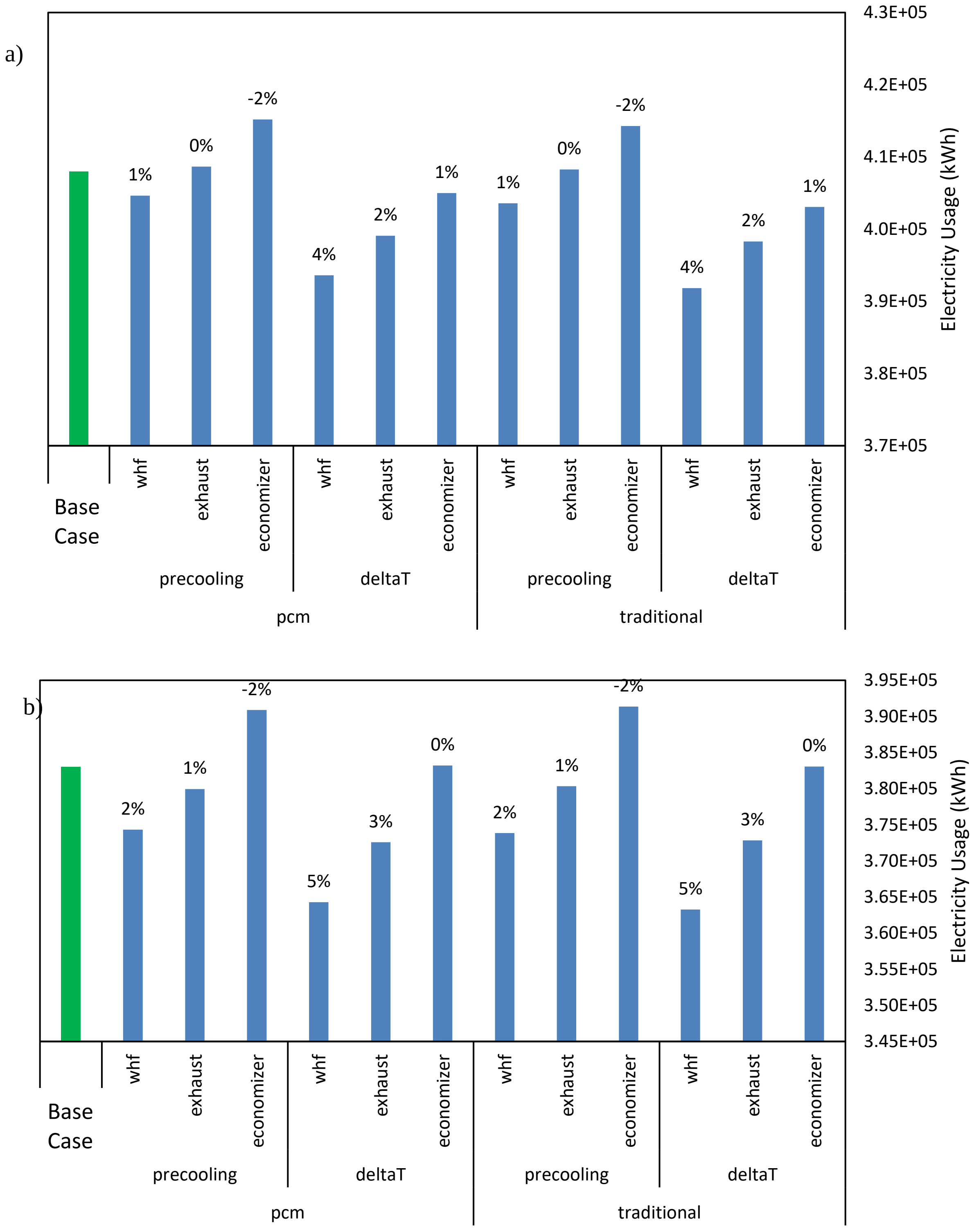
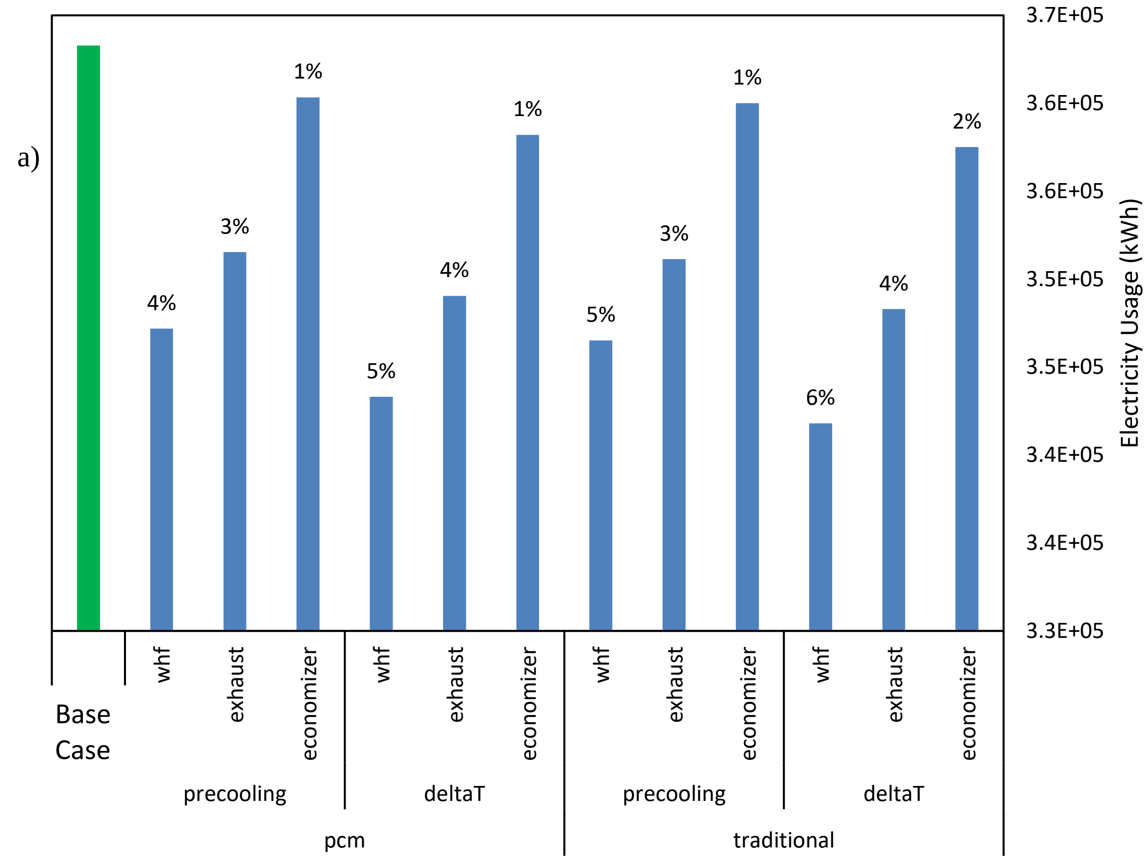


Figure 20. The effects of nighttime ventilation on whole-building energy usage for (a) Phoenix and (b) Houston.

3.4 EFFECT OF VENTILATION COOLING IN COLD CITIES

3.4.1 The Effect of Nighttime Ventilation on Whole-Building Energy Usage

As with the hot cities, the simple on-off control cases are not considered in the cold cities owing to nighttime temperatures, which in these cases are significantly lower. Figure 21 shows the effect of nighttime ventilation on whole-building energy usage for Chicago and Denver. Interestingly their results are slightly better than those of hot cities. In Chicago, the maximum savings observed are 6% and 4% for whole-house and kitchen exhaust fans, respectively, in concrete construction. For Denver, the maximum savings observed are 7% and 5% for whole-house and kitchen exhaust fans, respectively, in traditional construction. This pattern is observed mainly because of colder nighttime temperatures in the summer in these cold cities. The savings are slightly higher for traditional concrete construction. Much like with the hot cities, savings due to ventilation are significantly larger in all cases than savings owing to economizers.



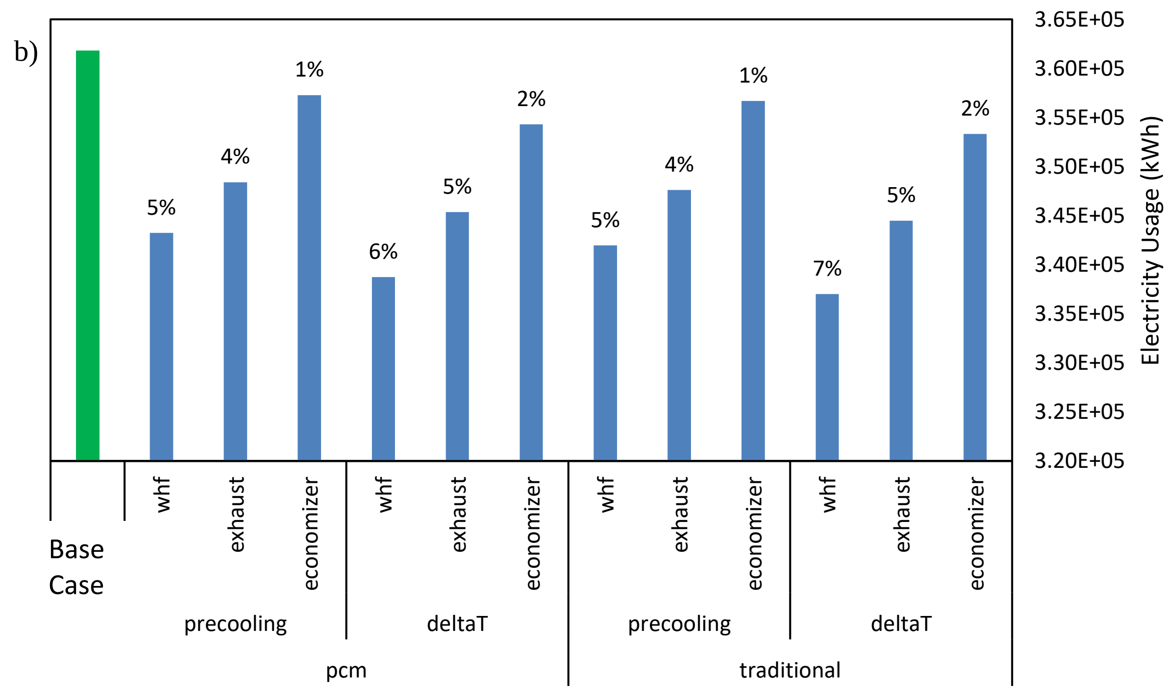


Figure 21. The effect of nighttime ventilation on whole-building energy usage for (a) Chicago and (b) Denver.

4. CONCLUSION

This study conducted a series of parametric simulations to understand the effect of TES-aided nighttime ventilation in multifamily buildings. The study results show that the use of nighttime ventilation aided with TES can assist considerably in minimizing building energy usage and peak demand in moderate-climate cities, where the nighttime air temperature is moderately cool but not so cold as to cause any heating penalty. The study considered six cities, with two each representing hot (Phoenix and Houston), moderate (Los Angeles and Atlanta), and cold (Chicago and Denver) regions.

In general, the effect of nighttime ventilation is most visible in moderate cities. The nighttime air temperature is neither too hot nor too cold in these regions; therefore, use of TES enables storage of cold energy during the nighttime (with the help of ventilation) and use of that energy during the daytime. Furthermore, staged precooling can minimize peak demand by about 16% without adding much penalty while precooling. Among the considered locations, Los Angeles has a higher rate of savings owing to more nights with moderately cold outdoor air temperatures. In the case of Atlanta, the nighttime temperature is not as moderate (or within the thermostatic setpoint) as that in Los Angeles, so savings are lower. A comparison between whole house fan and exhaust fan shows that savings are higher for whole-house fans, yet kitchen exhaust fans have a noticeable impact on electricity savings.

Exhaust fans can be installed in multifamily buildings in moderate climates without significant control systems because of their lower ventilation flow rate and the relatively favorable outdoor conditions. However, in the case of whole-house fans, a control strategy for operation is required even for moderate regions to avoid a penalty caused by higher ventilation flow rates. In Los Angeles, with a proper control strategy, a whole-house fan and an exhaust fan can reduce cooling electricity by 94% and 74%, respectively, and fan electricity by 31% and 15%, respectively. However, when accounting for total electricity (including other base loads), the savings are up to only 9%. Interestingly, both ventilation systems perform better than the economizer performs.

Savings for cases in hot and cold cities are considerably lower than those in moderate cities, mainly because the benefit of nighttime ventilation occurs only in nonextreme weather months. In cold cities, nighttime ventilation is useful in all seasons except winter; conversely, nighttime ventilation is useful in hot cities in all seasons except summer. Therefore, implementing nighttime ventilation aided with TES in these regions requires inclusion of a control system that activates nighttime ventilation only when the outdoor conditions are favorable. For these regions, irrespective of the ventilation system flow rate, a control strategy for operating ventilation is required to avoiding penalties. The magnitude of savings is based on the number of favorable days for nighttime ventilation strategies. In all cases, a whole-house fan offers the greatest savings, followed by exhaust fans with a slightly lower savings percentage. Using a whole-house fan, savings in the various locations are as follows: Denver, up to 7%; Chicago, 6%; Phoenix, up to 4%; and Houston, 5%. The results show that the economizer is the least efficient of the three options studied.

In summary, implementation of TES-aided nighttime ventilation with proper control strategies (e.g., ΔT ventilation cases or staged precooling, which were used in this study) can significantly increase the energy efficiency of multifamily buildings. This technology can help homeowners reduce energy usage and, thereby, yield a reduction in peak demand. These study results show that TES-aided nighttime ventilation can be implemented in most locations with proper control strategies; however, the magnitude of reduction in energy savings varies based on the number of favorable days for nighttime ventilation cooling. Moreover, TES-aided nighttime ventilation can assist in (1) minimizing carbon emissions by increasing energy usage when renewable energy is available from the grid and (2) minimizing energy use during periods when the grid emits more carbon dioxide.

5. ACKNOWLEDGEMENT

This material is based upon work supported by DOE’s Office of Science and BTO. This research used resources of ORNL’s Building Technologies Research and Integration Center (BTRIC), which is a DOE Office of Science User Facility. This manuscript has been authored by UT-Battelle LLC under contract DEAC05-00OR22725 with DOE. The US government retains and the publisher, by accepting the article for publication, acknowledges that the US government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this manuscript, or allow others to do so, for US government purposes.

REFERENCES

[1] H. Sha and D. Qi, "Investigation of mechanical ventilation for cooling in high-rise buildings," *Energy and Buildings*, vol. 228, p. 110440, 2020/12/01/ 2020, doi: https://doi.org/10.1016/j.enbuild.2020.110440.

[2] (2022). *Annual Energy Outlook*. [Online] Available: https://www.eia.gov/outlooks/aeo/pdf/aeo2020.pdf

[3] U. Berardi and P. Jafarpur, "Assessing the impact of climate change on building heating and cooling energy demand in Canada," *Renewable and Sustainable Energy Reviews*, vol. 121, p. 109681, 2020.

[4] D. P. Albuquerque, N. Mateus, M. Avantaggiato, and G. C. da Graça, "Full-scale measurement and validated simulation of cooling load reduction due to nighttime natural ventilation of a large atrium," *Energy and Buildings*, vol. 224, p. 110233, 2020.

[5] Y. Hu, P. K. Heiselberg, and R. Guo, "Ventilation cooling/heating performance of a PCM enhanced ventilated window - an experimental study," *Energy and Buildings*, vol. 214, p. 109903, 2020/05/01/ 2020, doi: https://doi.org/10.1016/j.enbuild.2020.109903.

[6] B. Vidrih, C. Arkar, and S. Medved, "Generalized model-based predictive weather control for the control of free cooling by enhanced night-time ventilation," *Applied Energy*, vol. 168, pp. 482-492, 2016.

[7] S. Medved, M. Babnik, B. Vidrih, and C. Arkar, "Parametric study on the advantages of weather-predicted control algorithm of free cooling ventilation system," *Energy*, vol. 73, pp. 80-87, 2014/08/14/ 2014, doi: https://doi.org/10.1016/j.energy.2014.05.080.

[8] Y. Zhang, X. Wang, and E. Hu, "Optimization of night mechanical ventilation strategy in summer for cooling energy saving based on inverse problem method," *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy*, vol. 232, no. 8, pp. 1093-1102, 2018.

[9] Z. Wang, L. Yi, and F. Gao, "Night ventilation control strategies in office buildings," *Solar Energy*, vol. 83, no. 10, pp. 1902-1913, 2009.

[10] P. Devaux and M. M. Farid, "Benefits of PCM underfloor heating with PCM wallboards for space heating in winter," *Applied Energy*, vol. 191, pp. 593-602, 2017/04/01/ 2017, doi: https://doi.org/10.1016/j.apenergy.2017.01.060.

[11] L. Klimeš *et al.*, "Computer modelling and experimental investigation of phase change hysteresis of PCMs: The state-of-the-art review," *Applied Energy*, vol. 263, p. 114572, 2020/04/01/ 2020, doi: https://doi.org/10.1016/j.apenergy.2020.114572.

[12] J. A. Prem Anand Jayaprabha, X. Liu, L. Wang, and M. Malhotra, "An assessment of existing barriers to market adoption of thermal energy storage in buildings based on interviews with stakeholders," United States, 2024-01-01 2024, Research Org.: Oak Ridge National Laboratory (ORNL), Oak Ridge, TN (United States), Sponsor Org.: USDOE Office of Energy Efficiency and Renewable Energy (EERE), doi: Conference: 2024 ASHRAE Winter Conference - Chicago, Illinois, United States of America - 1/20/2024 5:00:00 AM-1/24/2024 5:00:00 AM. [Online]. Available: https://www.osti.gov/biblio/2320376[Online]. Available: https://www.osti.gov/servlets/purl/2320376

[13] E. Documentation, *Engineering Reference*: The , Department of Energy, 2019.

[14] J. Anand, "Potential impact of work from home jobs on residential energy bills: A case study in phoenix, AZ, USA," *Journal of Building Engineering*, vol. 68, p. 106063, 2023/06/01/ 2023, doi: https://doi.org/10.1016/j.jobe.2023.106063.