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Paper Session 13

Evaluation of the Thermal Resilience of Residential Buildings with PCM Enhanced Envelope Under Different Climate Zone

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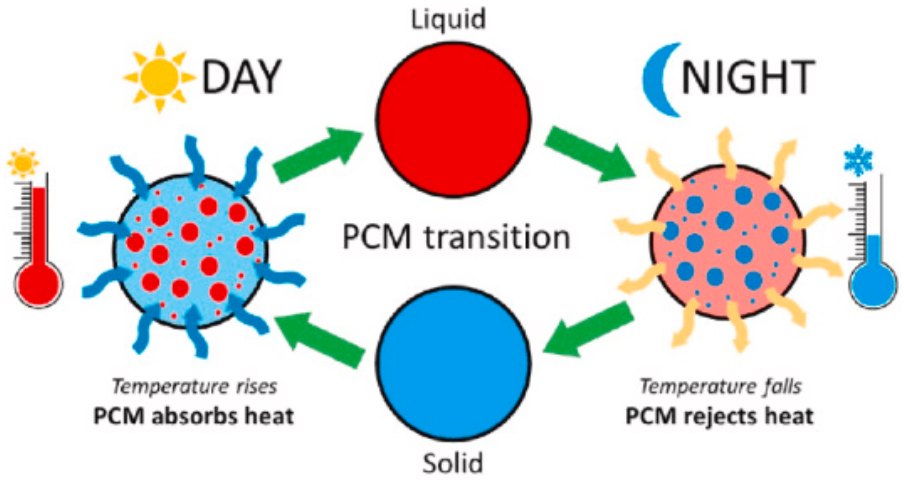
Learning Objectives

- Understand the effectiveness of PCM enhanced building envelope on energy savings and thermal resilience.
- Understand the melting temperature and thickness of PCM could impact the effectiveness of PCM.

Introduction

- Due to more frequent, intense, and longer duration extreme weather events [1] and people spend approximately 90% [2] of their time in indoor environments, the **building thermal resilience** study is significant.
- Thermal mass has been recognized as an effective passive strategy to mitigate overheating in buildings.
- Compared to traditional materials, **Phase Change Materials (PCMs)** have higher heat storage capacity [3-4].



Contribution

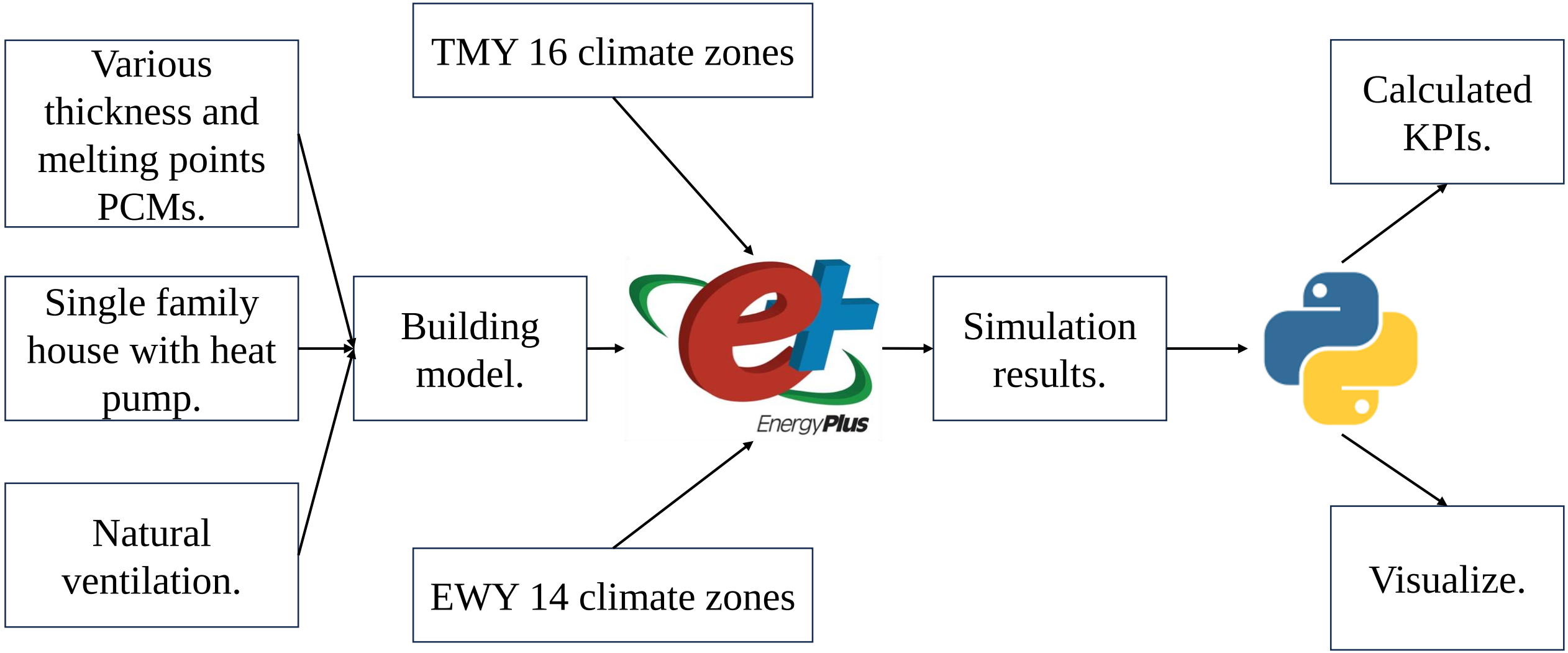
Previously studies:

- Selected a specific thickness, melting temperature or climate zone.
- Relied on TMY weather files for simulations of regular weather conditions.
- Lacked integrating PCMs with other measures, e.g., natural ventilation, for thermal resilience studies.

This study:

- Conduct a **comprehensive parametric study** of various PCM thickness and melting points under 16 ASHRAE climate zones in U.S.
- Use **future extreme warm year (EWY)** weather data for assessing thermal resilience, considering **power outage scenarios**.
- **Combine natural ventilation** with PCMs.

Method


Various thickness and melting points PCMs.
Single family house with heat pump.
Natural ventilation.
TMY 16 climate zones
EWY 14 climate zones
Building model.
EnergyPlus
Simulation results.
Calculated KPIs.
Visualize.

Case description

	Baseline	Weather file	Thermal resilience measures		
			PCM enhanced envelope		Night Ventilation
			MT (°C)	Thickness (cm)	
Case 1	DOE residential building prototype.	TMY	14-30 (interval 1)	0.5-3 (interval 0.5)	No
Case 2	DOE residential building prototype with **power outage** during heat wave.	**EWY**	18-34 (interval 1)	0.5-3 (interval 0.5)	No
Case 3	DOE residential building prototype with **power outage** during heat wave.	**EWY**	28	3	**Yes**

Building model information

Plan area	112 m^2 (1205.6ft^2)
Foundation type	Heated basement
Aspect ratio	1.33
Window to wall ratio	N(13%), S(13%), E(17%), W(17%)
Exterior walls, roof, and U-value	Vary by climate
Glazing U-value and SHGC	Vary by climate
Infiltration rate	Varies by climate
HVAC system	Heat pump -sized by EnergyPlus
Thermostat setpoints	22°C(71.6°F) for heating, 24°C(75.2°F) by cooling

PCM properties

Latent Heat	10000 J/kg
Liquid State Thermal Conductivity	1.5 W/m K
Liquid State Density	2200 kg/m^3
Liquid State Specific Heat	2000 J/kg K
Solid State Thermal Conductivity	1.8 W/m K
Solid State Density	2300 kg/m^3
Solid State Specific Heat	2000 J/kg K

Key performance indicators

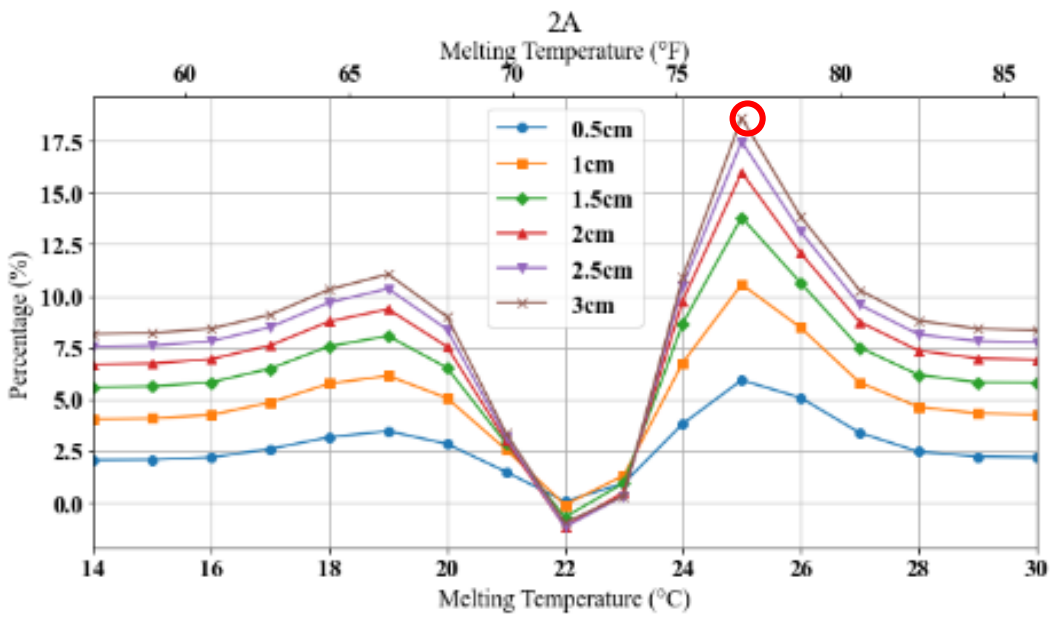
KPIs	Equation	Case
Energy savings percentage	$\eta = \frac{E_b - E_p}{E_b} \times 100$	Case 1
Unmet hours		Case 1
Indoor overheating degree	$IOD = \frac{\sum_{h_o} \left\| T_i - T_c \right\|}{h_o}$	Case 2 & Case 3
Ambient warmness degree	$AWD = \frac{\sum_{h_o} \left\| T_o - T_f \right\|}{h_o}$	Case 2 & Case 3
Overheating escalation factors	$OEF = \frac{IOD}{AWD}$	Case 2 & Case 3

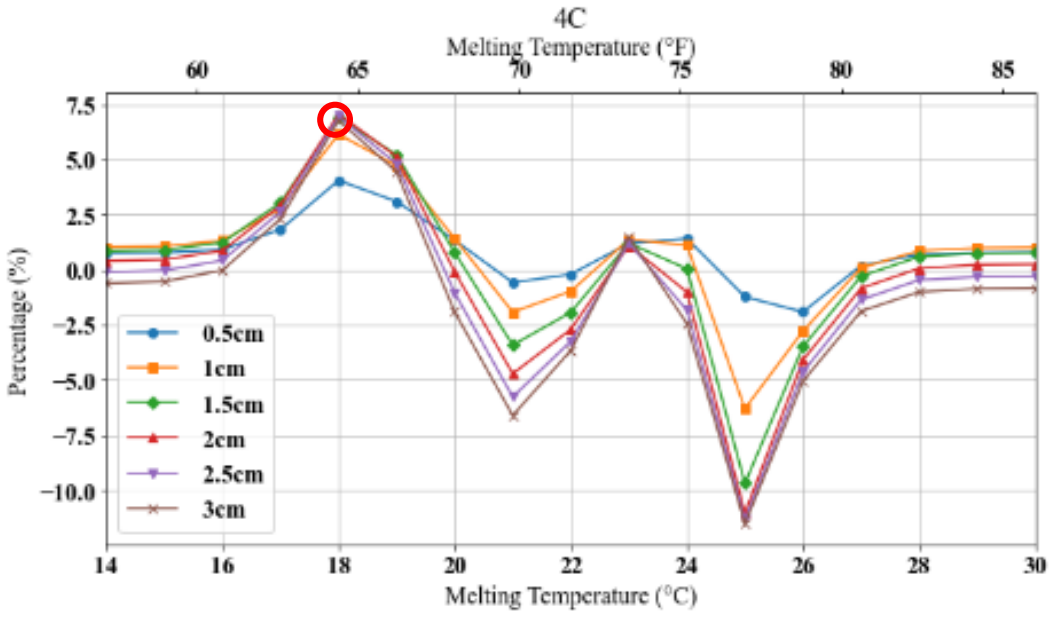
Case 1: Energy performance with PCMs

- In this case, the **improvement in energy efficiency of PCM-enhanced building envelopes** under various melting points (14-30°C(57.2-86°F)) and thickness (0.5-3cm) has been verified.

Case 1: Results of energy savings

- In most cases, as the thickness of the PCM layer increases, **energy savings increase, but the energy savings per centimeter (ESPC) decrease**.
- The **optimal melting temperature** of PCM **varies** across climate zones.
- This suggests that the **cost-effectiveness** of PCM thickness should be carefully evaluated when using PCM to improve energy efficiency.





Case 1: Results of unmet hours

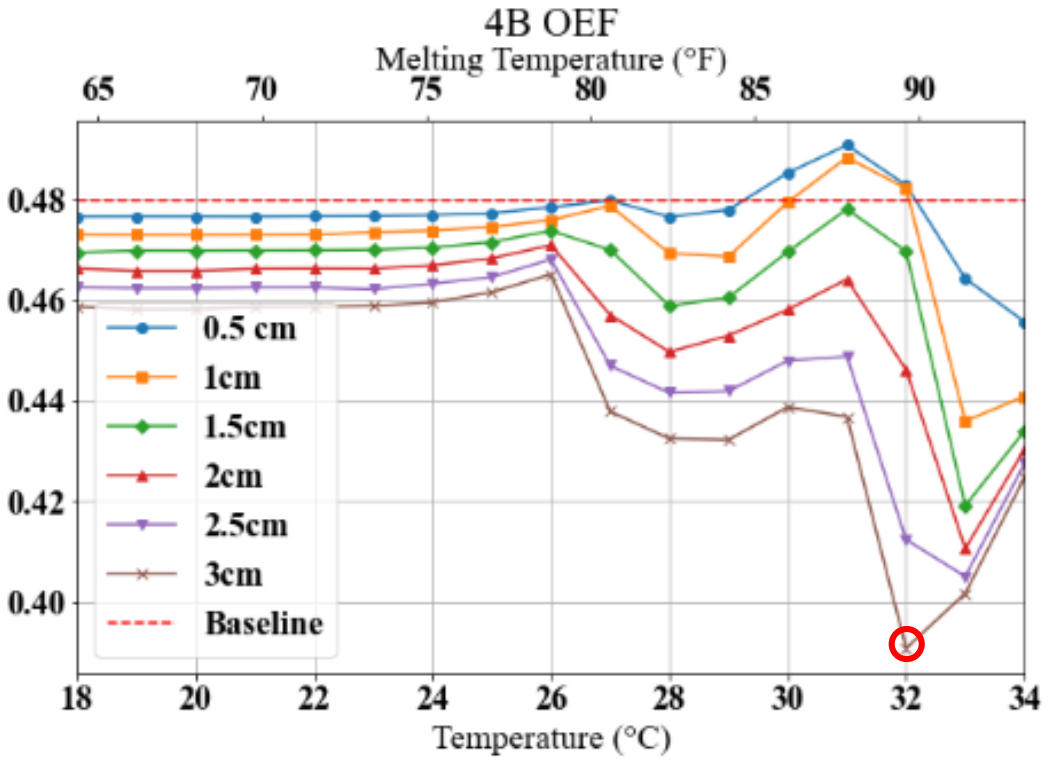
	Baseline (h)		PCM (h)	
	Heating	Cooling	Heating	Cooling
1A	2.26	71.56	0.45	35.15
2A	13.26	**114.36**	51.46	**7.31**
2B	21.72	564.88	13.09	506.76
3A	30.4	221.72	16.12	149.15
3B	44.12	197.36	26.37	191.7
3C	51.45	**49.97**	33.96	**2.97**
4A	72.2	54.9	81.6	35.3
4B	127.71	87.93	29.94	83.27
4C	63.55	29.55	24.9	23.61
5A	448.53	6.95	883	3.47
5B	661.98	41.9	610.78	37.9
5C	72.99	9.77	30.65	6.49
6A	4427.16	14.41	4157.96	1.3
6B	1627	53.42	2645.17	43.64
7	2141.5	8.63	1794.33	0.71
8	487.79	0.59	334.98	0.1

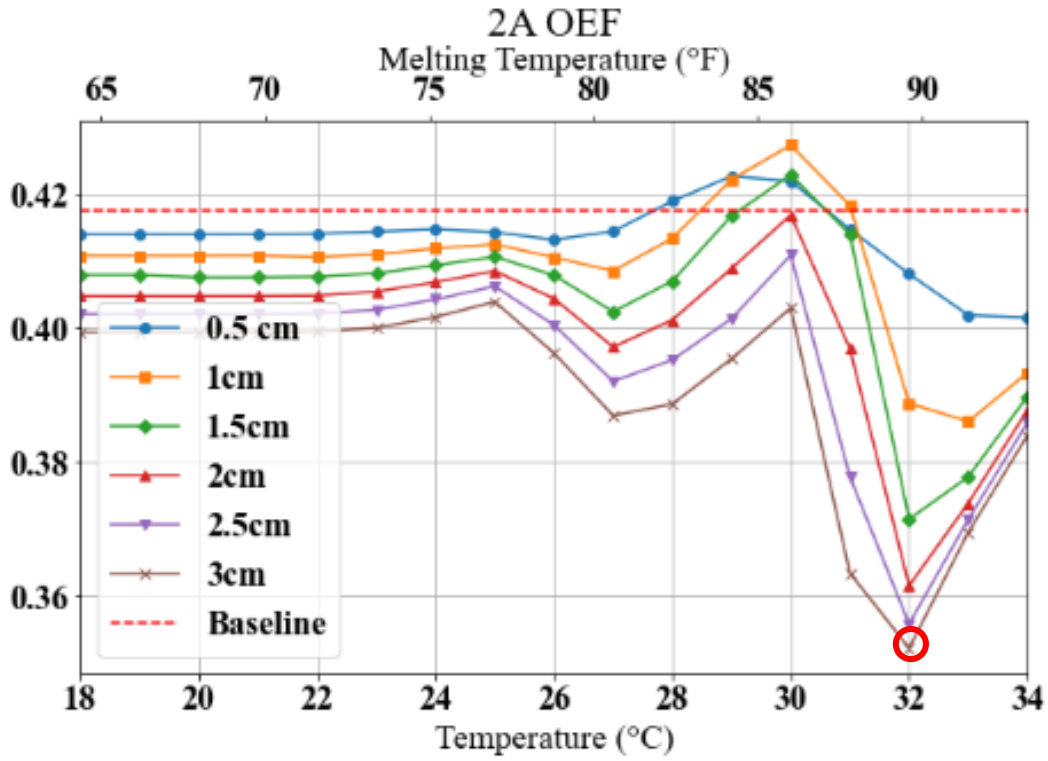
Case 2: Thermal resilience performance with PCMs

- **Power outages** are common during heat waves in summer, often caused by severe weather events. For example, during the blistering heat wave that scorched the Pacific Northwest in 2021, power equipment failed under the extreme heat, triggering rolling blackouts for tens of thousands as temperatures soared above 37.8°C(100.04°F) [5].
- In this case, we modified the models' schedules, for example cooling schedule and heating schedule, to assess the **thermal resilience of PCM integrated buildings** by simulating the **power outage scenario during a heat wave**. The heat wave periods vary across different locations.

Case 2: Results of thermal resilience

- The KPIs indicated that, the buildings' **thermal resilience during a heat wave with power outage can be improved** for each climate zone **with careful selection of PCMs**.
- For example, the Overheating escalation factors (OEF) in climate zone 4B decreased from 0.48 in the baseline to 0.39 with PCMs, representing an **18.5% reduction**.





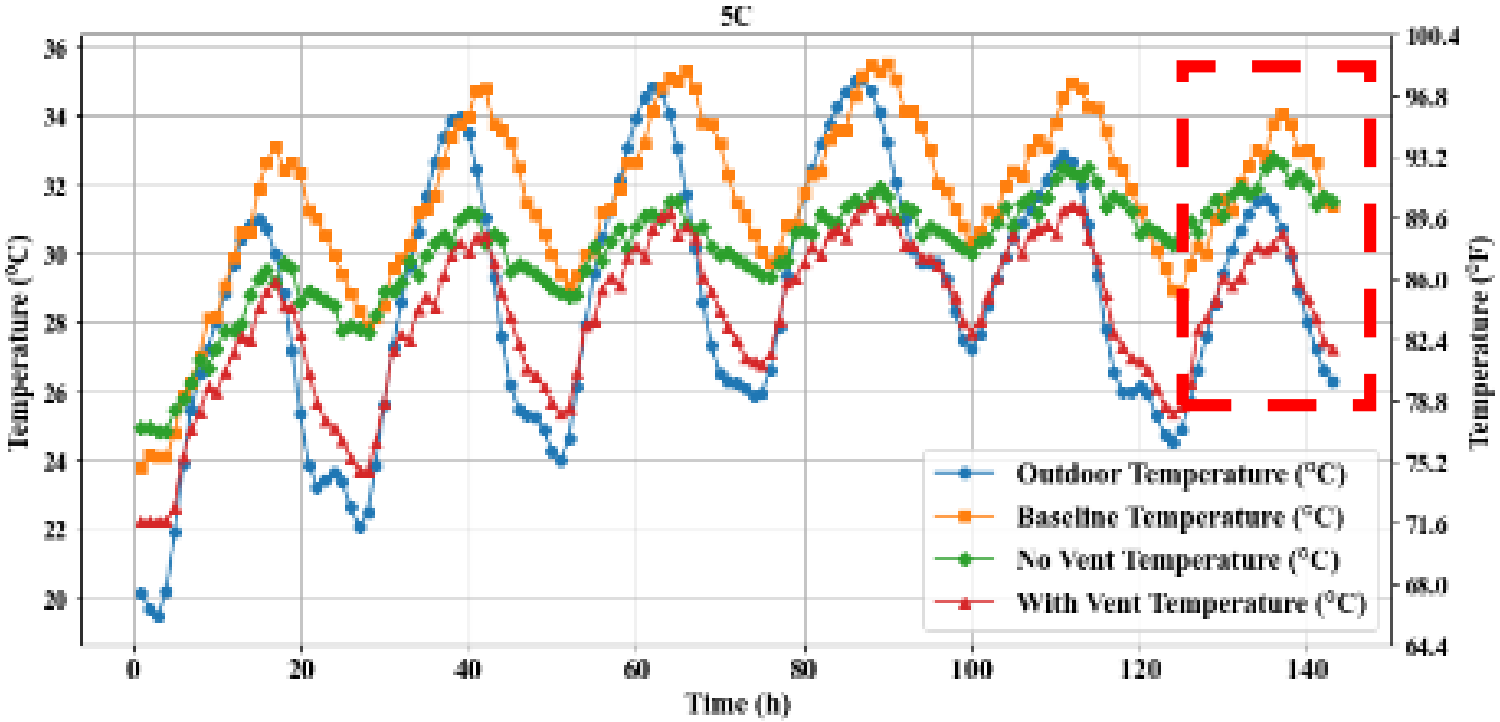
Case 3: Enhance thermal resilience performance by combining NV with PCM

- When analyzing indoor temperatures in Case 2, we found that while PCM was effective at the beginning of the heat wave, its **effectiveness diminished after several days**, **due to the PCM not recharging under prolonged high temperatures**.
- To address this, we **combined night natural ventilation with PCMs** to further enhance the potential of PCM in improving buildings' thermal resilience.
- Natural ventilation has been integrated into our model by adding schedules and modifying '*AirflowNetwork*'.

Case 3: Performance with NV

- Integrating Natural Ventilation leads to a **0-4.4°C reduction of the daily average indoor temperature** at the last day of the heat wave events compared to buildings with a PCM layer but without night ventilation.

- For example, in climate zone 5C, the daily average indoor temperatures **on the ninth day** are **31.5°C (88.7°F)** without natural ventilation, and **28.2°C (82.8°F)** with natural ventilation.



Case 3: Results of KPIs

Climate zone	Without night ventilation			Night ventilation		
	UH (h)	IOD(°C)	OEF	UH (h)	IOD (°C)	OEF
1A	138	3.52	0.29	130	2.89	0.23
2A	144	6.35	0.4	143	5.42	0.37
2B	216	9.6	0.44	215	9.59	0.55
3A	95	5.62	0.36	95	5.1	0.35
3B	240	7.9	0.42	239	6.92	0.42
3C	159	2.46	**0.28**	114	1.41	**0.13**
4A	117	3.88	0.31	118	3.33	0.26
4B	144	6.94	0.44	143	5.5	0.35
4C	186	5.93	0.48	166	4.24	0.29
5A	144	5.5	0.41	143	4.31	0.3
5B	167	7.01	0.39	167	6.32	0.35
5C	137	4.14	**0.39**	120	2.49	**0.18**
6A	118	5.6	0.38	118	4.93	0.34
6B	119	5.96	0.42	118	4.16	0.28

Conclusion

- PCM-enhanced building envelopes can **achieve energy savings of 2.1-36.5%** across 16 climate zones.

- Adding a PCM layer to residential buildings can **significantly enhance thermal resilience during heat waves with power outages**, offering a promising method to maintain a healthy and safe indoor environment.

- **Combining natural ventilation** at night with PCM-enhanced building envelopes can **further enhance the building thermal resilience** especially with power outages during heat waves.

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Questions

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