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Maximizing Cooling Energy Savings in Buildings with Climate Change: The Potential of Phase Change Materials and Ventilation Strategies

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Masters Thesis Defense Presentation

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Table of Content

Introduction

How Climate Change Influences our world?

- Around 4.8°C increase in the temperature of the earth is forecasted by the end of this century [1].

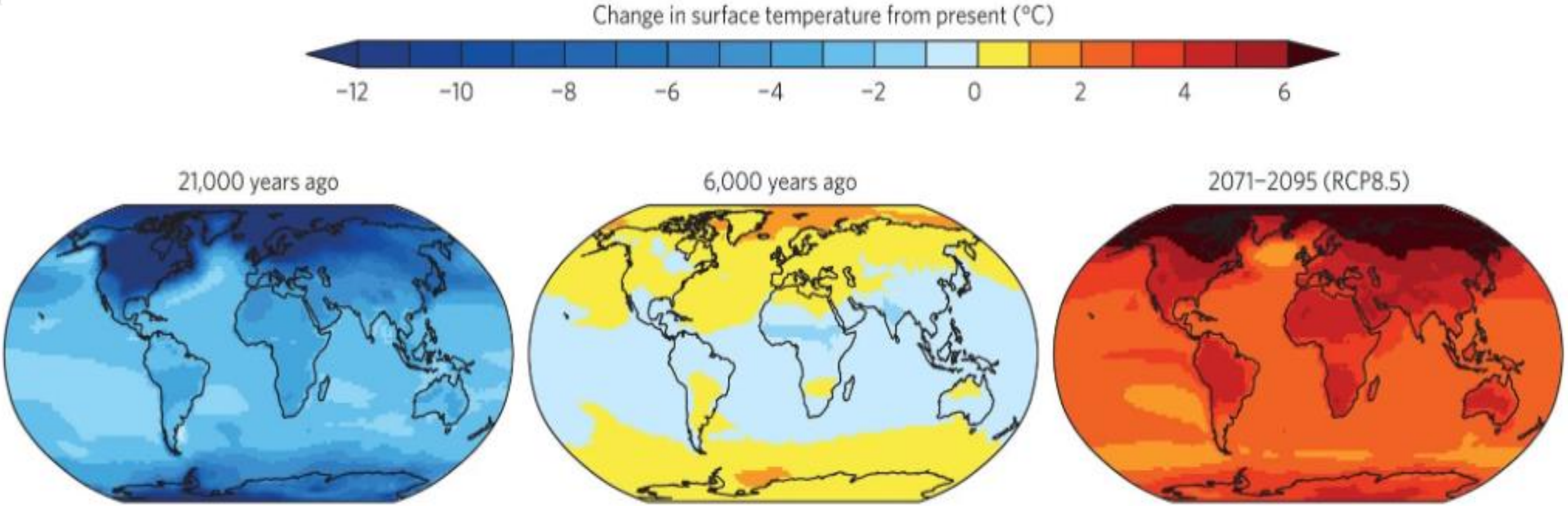

Fig.1 Model-simulated global temperature anomalies [2].

- Anthropogenic greenhouse gases are mainly responsible for climate change [1].

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Introduction

What is the energy consumption and environmental impact of the building sector?

- The building sector consumes more than one-third of global energy usage [3].
- The buildings sector owns over 30% share of the total greenhouse gasses [3].

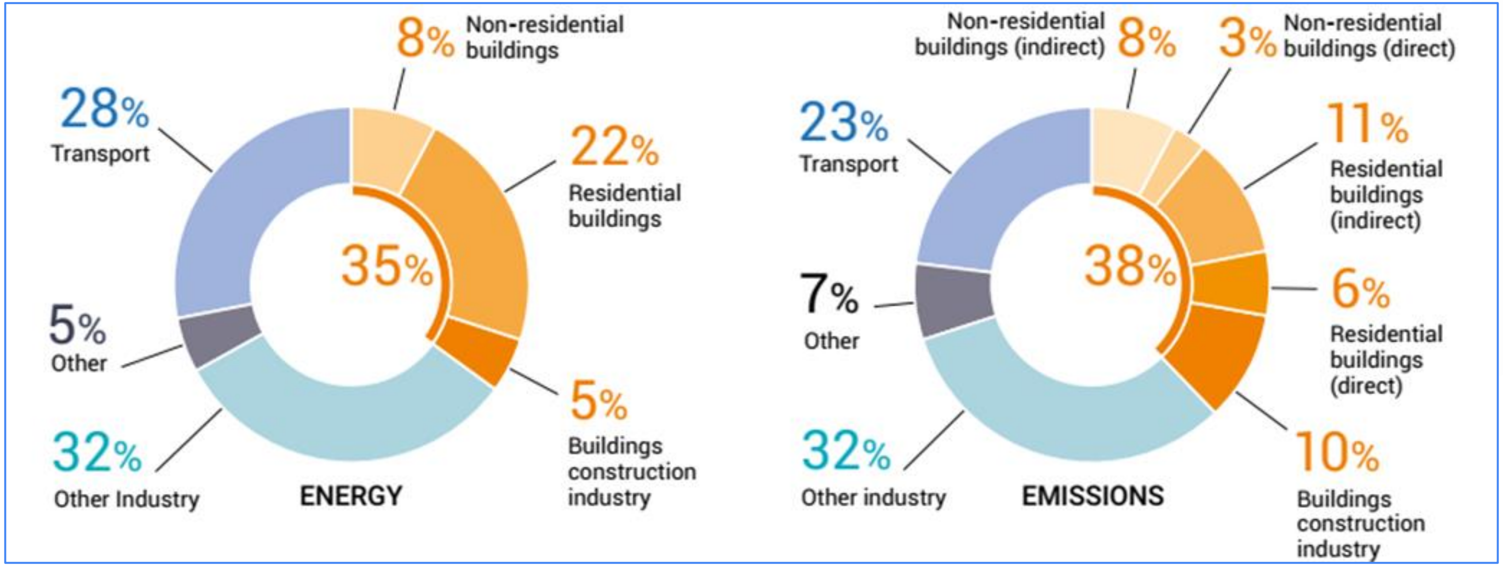


Fig.2 Global share of buildings and construction final energy and emissions, 2019 (Sources: IEA 2020; IEA 2020b) [4].

Introduction

What would be the impact of climate change on the energy consumption of the building sector?

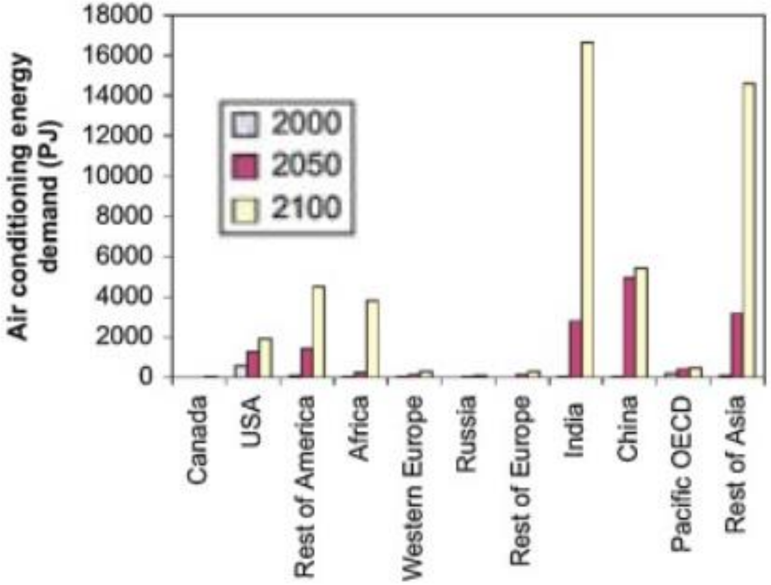
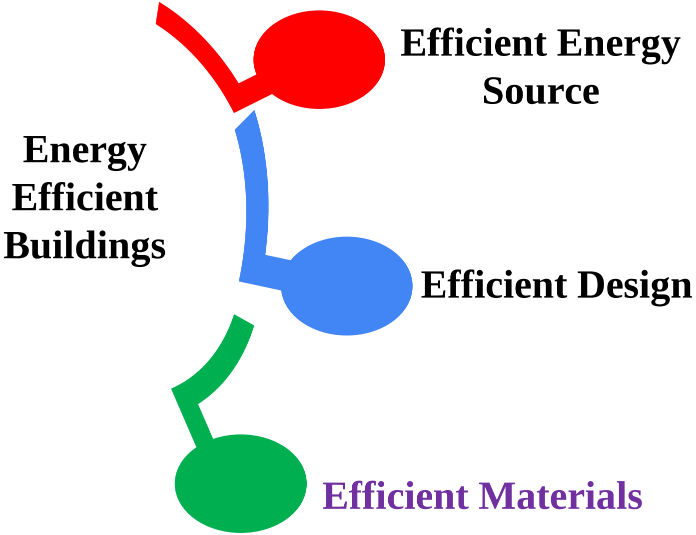


Fig.3 Residential building cooling energy demand in present and future [6]

- Currently the building sector consumes almost 40% of the total global energy [5].
- Anticipated increase in building cooling energy is 72% by 2100 [6].

Introduction

How to achieve energy efficiency in the building?



Energy Efficient Buildings

Efficient Energy Source

Efficient Design

Efficient Materials

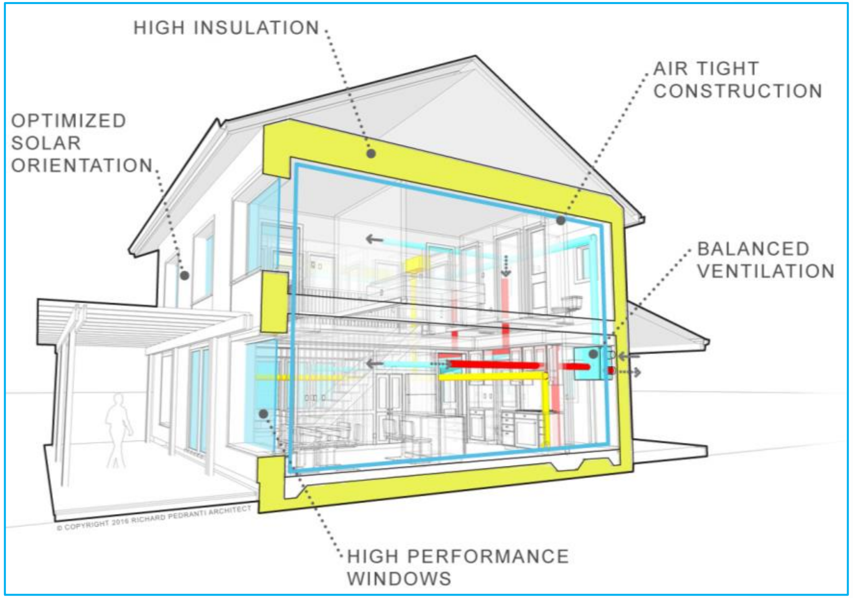


Fig 4. Energy-efficient building design measures [7].

Introduction

What is the material?

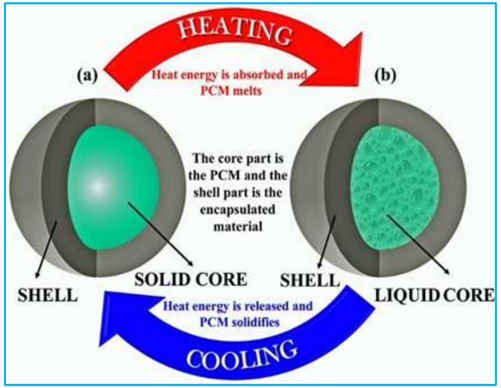


Fig. 5. PCM working mechanism [8].

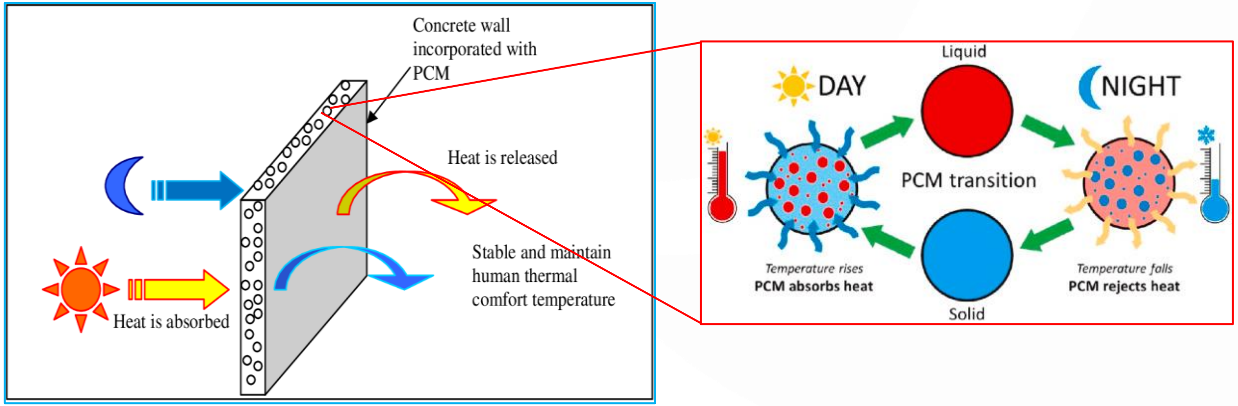


Fig. 6. Working principles of PCM [9-10]

- **Phase Change Materials (PCM):** PCMs absorb and release the energy in the process of phase change.

Literature Review

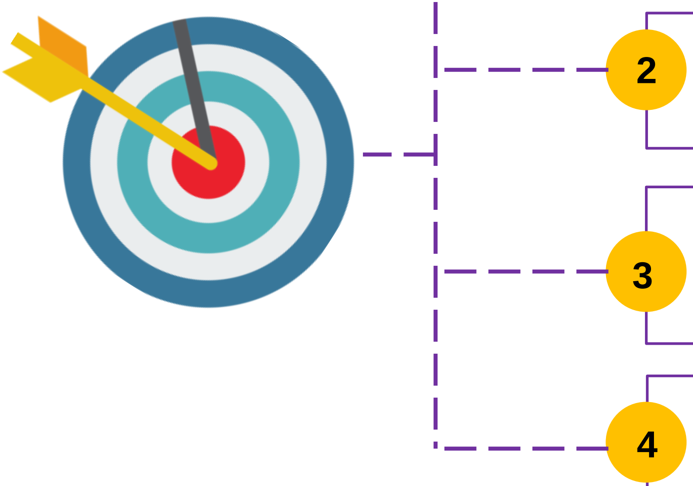
- The cooling demand will increase by 72% in the next century and the impact will be more pronounced in developing countries [6].
- The response of PCM when integrated into buildings is highly complex and depends upon external and internal environmental conditions [11].
- Saffari et al. performed an optimization of PCM for building energy efficiency in 18 different zones and concluded that, significant energy can be achieved with a proper selection of PCM [12].
- Ramakrishnan et al. investigated the PCM and night ventilation (PCM +NV) combination for reducing heat risk in buildings and the results evidence up to 32% reduction discomfort hours [13].
- Prabhakar et al. implemented smart natural ventilation in combination with PCM and argued that better control of natural ventilation yields higher energy savings [14].

Problem Statement

What are the problem?

- What would be the impact of PCM implementation on cooling energy saving with climate change?
- What would be the optimum PCM for different climate zones considering climate change?
- What would be the exact latent heat exploitation of PCM during energy storage release?
- What would be the impact of combination of PCM and different ventilation strategies?

Research Objectives

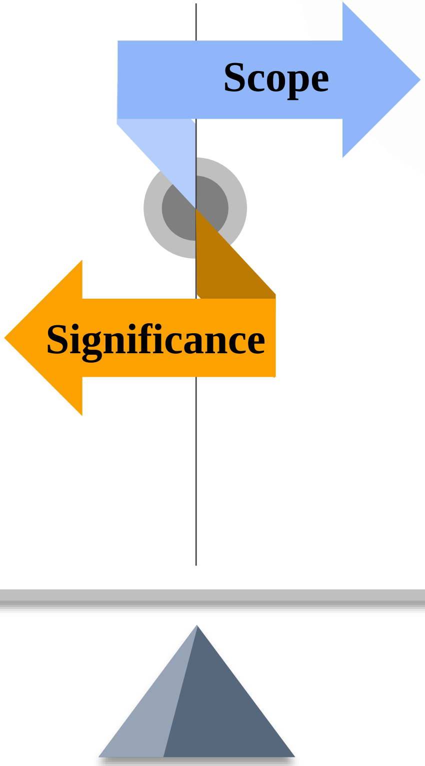


1. To evaluate the impact of PCM integration into building envelop for energy efficiency with climate change.
2. To find the optimum PCM coupled under different indoor boundary conditions for 39 cities in 13 climate zones.
3. To evaluate the impact of natural ventilation strategies and PCM combination on the cooling energy savings.
4. To Propose novel indicators that can quantify the performance of PCM based on the latent heat exploitation of PCM.

Research Significance and Scope

- This study strengthens the idea of implementing energy efficiency technology in the future by evaluating the potential of PCM for cooling energy savings with climate change.

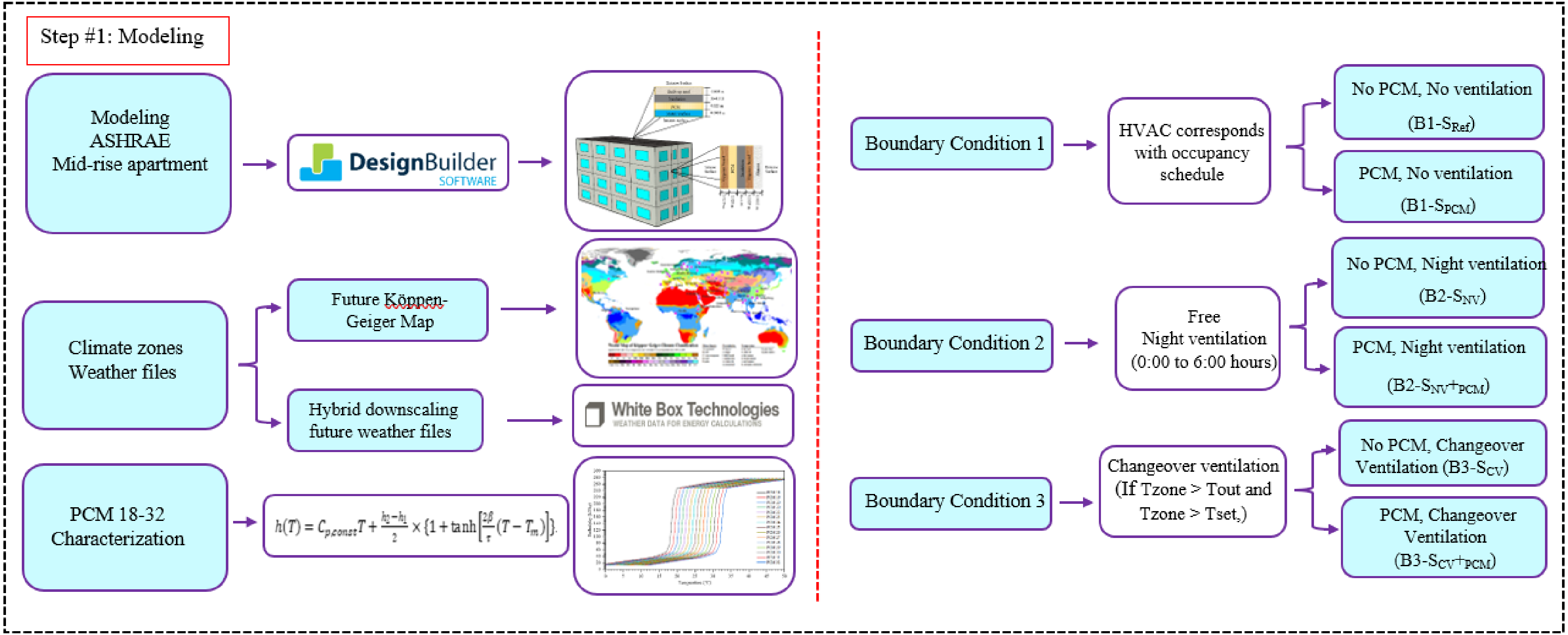
- The finding can be used as a guideline for energy-efficient building design in the future.



- The study is performed to evaluate the cooling energy efficiency considering only the summer period (Jun to August).

- The design parameters for PCM such as PCM layer thickness, building size, type, and occupancy were kept the same for all the indoor boundary conditions evaluated in this research.

Methodology



Step #1: Modeling

Modeling ASHRAE Mid-rise apartment → DesignBuilder SOFTWARE →

Climate zones Weather files → Future Köppen-Geiger Map →

Climate zones Weather files → Hybrid downscaling future weather files → White Box Technologies WEATHER DATA FOR ENERGY CALCULATIONS

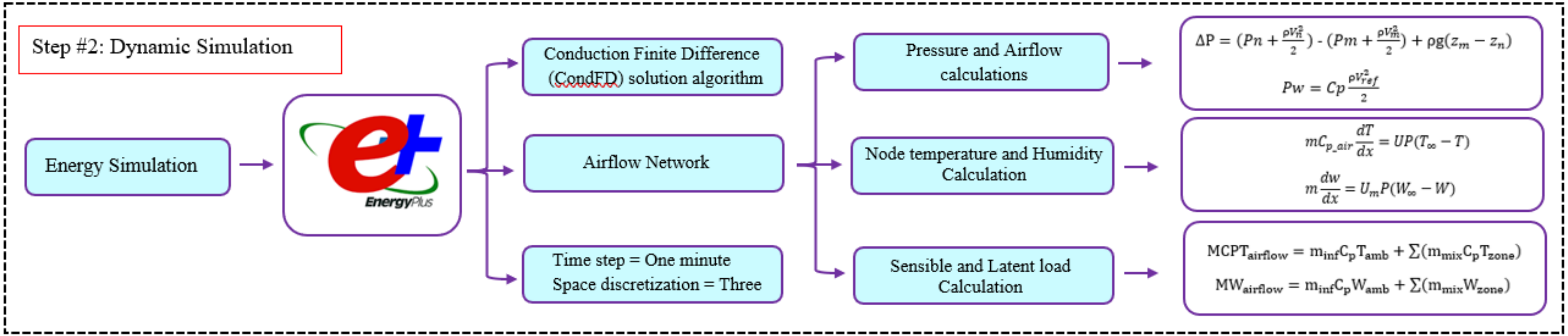
PCM 18-32 Characterization → $h(T) = C_{p,const}T + \frac{h_2-h_1}{2} \times \{1+\tanh[\frac{2\beta}{\tau}(T-T_m)]\}$ →

Boundary Condition 1 → HVAC corresponds with occupancy schedule →
- No PCM, No ventilation ($B1\text{-}S_{Ref}$)
- PCM, No ventilation ($B1\text{-}S_{PCM}$)

Boundary Condition 2 → Free Night ventilation (0:00 to 6:00 hours) →
- No PCM, Night ventilation ($B2\text{-}S_{NV}$)
- PCM, Night ventilation ($B2\text{-}S_{NV+PCM}$)

Boundary Condition 3 → Changeover ventilation (If Tzone > Tout and Tzone > Tset,) →
- No PCM, Changeover Ventilation ($B3\text{-}S_{CV}$)
- PCM, Changeover Ventilation ($B3\text{-}S_{CV+PCM}$)

Methodology…



Step #2: Dynamic Simulation

Energy Simulation

EnergyPlus

Conduction Finite Difference (CondFD) solution algorithm

Airflow Network

Time step = One minute
Space discretization = Three

Pressure and Airflow calculations

$$\Delta P = \left(Pn + \frac{\rho V_n^2}{2}\right) - \left(Pm + \frac{\rho V_m^2}{2}\right) + \rho g(z_m - z_n)$$

$$Pw = Cp\frac{\rho V_{ref}^2}{2}$$

Node temperature and Humidity Calculation

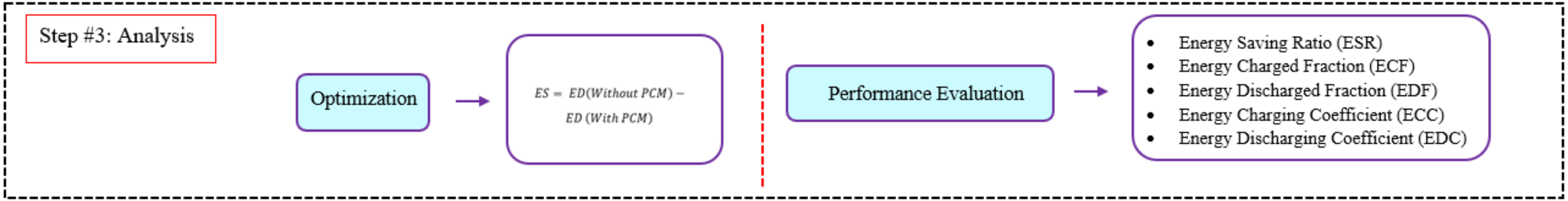
$$mC_{p\_air}\frac{dT}{dx} = UP(T_\infty - T)$$

$$m\frac{dw}{dx} = U_m P(W_\infty - W)$$

Sensible and Latent load Calculation

$$\mathrm{MCPT_{airflow}} = \mathrm{m_{inf}C_pT_{amb}} + \sum(\mathrm{m_{mix}C_pT_{zone}})$$

$$\mathrm{MW_{airflow}} = \mathrm{m_{inf}C_pW_{amb}} + \sum(\mathrm{m_{mix}W_{zone}})$$



Step #3: Analysis

Optimization

$$ES = ED(Without\ PCM) - ED\ (With\ PCM)$$

Performance Evaluation

- Energy Saving Ratio (ESR)
- Energy Charged Fraction (ECF)
- Energy Discharged Fraction (EDF)
- Energy Charging Coefficient (ECC)
- Energy Discharging Coefficient (EDC)

Methodology…

Climate Zones and Selection of Cities

- Future Köppen-Geiger Climate Classification Map [15].
- 13 Different Climate and zones 39 Representative Cities
- Future weather files for 2095 were obtained from Whitebox technology [16].

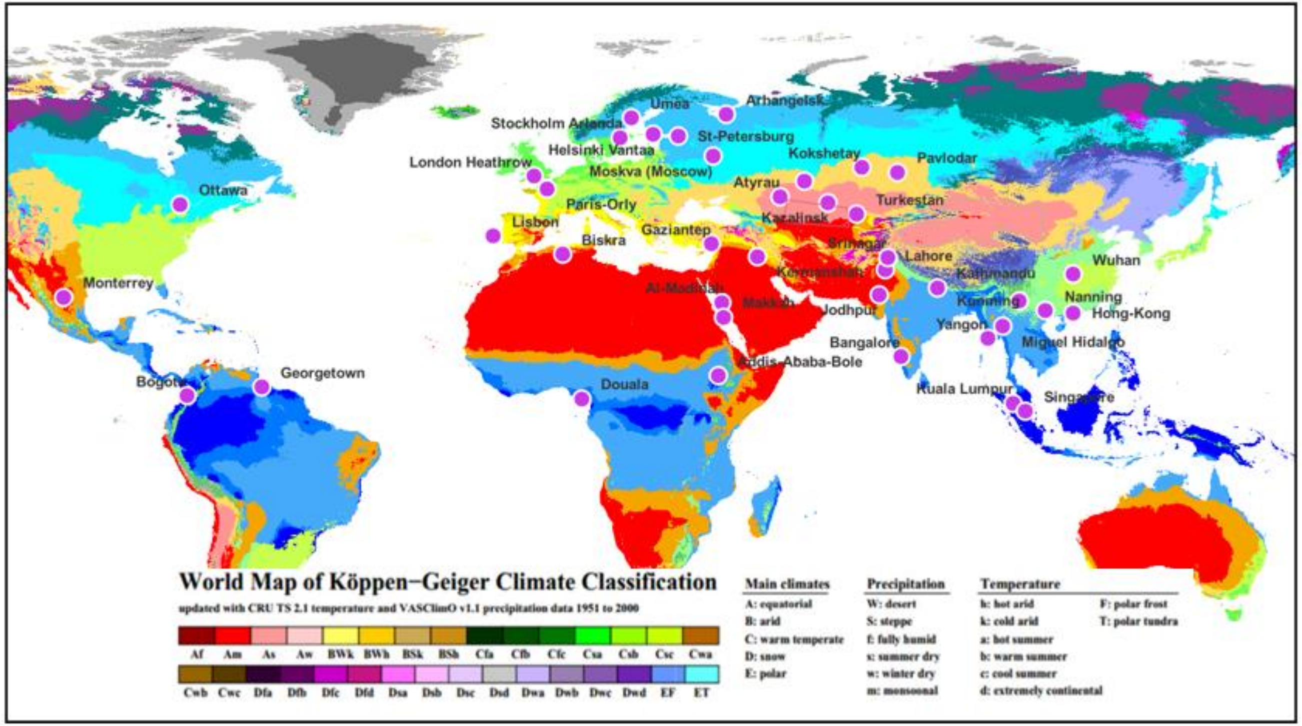


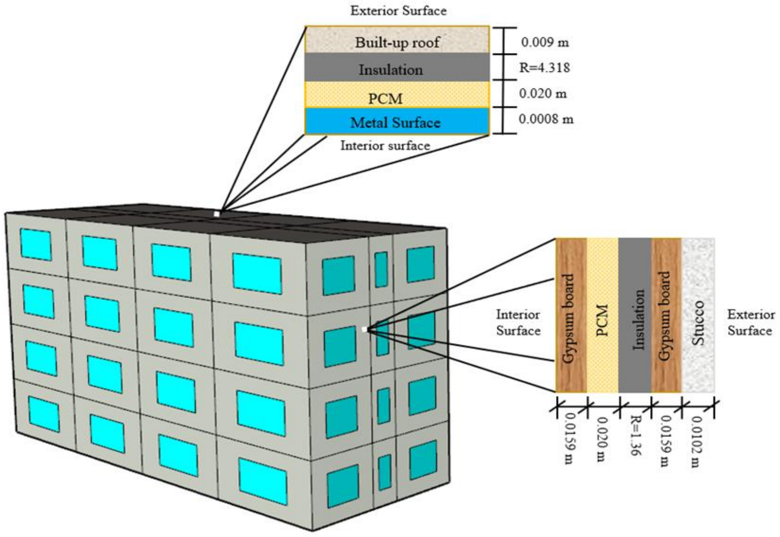
Fig.7. Future Köppen-Geiger Climate Classification Map [15].

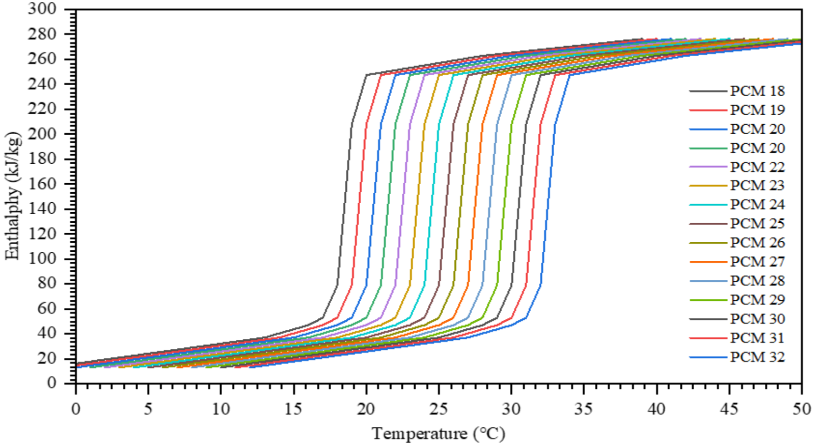
Methodology…

- **PCMs and Building Model Selection**

Building Model

- Mid-rise residential apartment building conforming ASHRAE Standard 90.1-2013.





PCM

- PCM with melting points ranging from 18°C to 32°C (PCM18 to PCM32).
- Latent heat storage capacity is 219kJ/kg.

Methodology…

- **Indoor boundary conditions**

Boundary Condition	Scenario	Building Condition	Nomenclature
1	a	No PCM, No ventilation	B1-S_{Ref}
	b	With PCM, No ventilation,	B1-S_{PCM}
2	c	No PCM, With free Night Ventilation	B2-S_{NV}
	d	PCM, With free Night ventilation	B2-S_{NV+PCM}
3	e	No PCM, With Changeover ventilation	B3-S_{CV}
	f	With PCM, With Changeover ventilation,	B3-S_{CV+PCM}

Methodology…

Numerical Simulation and Validation

- Energyplus uses the conduction finite difference (ConFD) solution algorithm.

$$\rho C_P \Delta x \frac{T_i^{j+1}-T_i^{j}}{\Delta t} = (k_W \frac{(T_{i+1}^{j+1}-T_i^{j+1})}{\Delta x} + k_E \frac{(T_{i-1}^{j+1}-T_i^{j+1})}{\Delta x}) \qquad (1)$$

$$C_p = \frac{h_{i.new}+h_{i.old})}{T_{i.new}+T_{i.old}} \qquad (2)$$

Where:

Cp	Specific heat capacity (kJ/kg-K)
ρ	Density(kg/m^3)
Δx	Layer thickness (m)
Δt	Calculation time step (s)
T	Node temperature (K)
h	Enthalpy (kJ/kg).
j+1	Simulation time step
i	Node being modelled
i+1	Adjacent nodes towards inner side
i-1	Adjacent nodes outer sides
k_W	thermal conductivity for the interface between increase node and *i+1* node
k_E	is thermal conductivity for the interface between *i* node and *i-1* node
j	Previous time step

Validation

Numerical Simulation

- The simulation of PCM in design builder is validated by using the experimental data of Cui et al.’s [10].

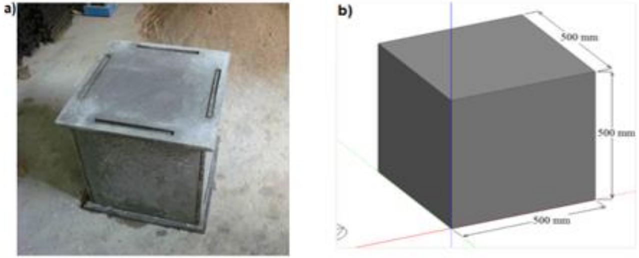


Fig. 8: a) Experimental model b) numerical model [17].

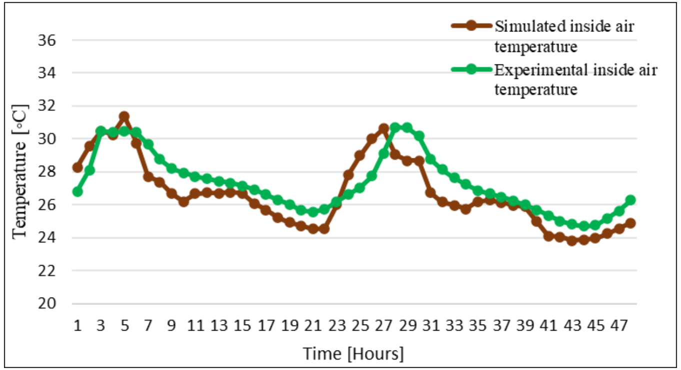


Fig. 9: Experimental versus numerical validation [17].

Methodology…

Optimization

The optimum PCM can be obtained by the following equations:

$$ES = EC_w - EC_P \qquad (1)$$

$$\mathrm{ESR_{pcm}} = \left(1 - \frac{\mathrm{CED_{pcm}}}{\mathrm{CED_{ref}}}\right) \times 100 \quad (2)$$

Where:

ES = Energy savings [kWh]

EC_w = Energy consumption without PCM incorporation into the building envelope [kWh]

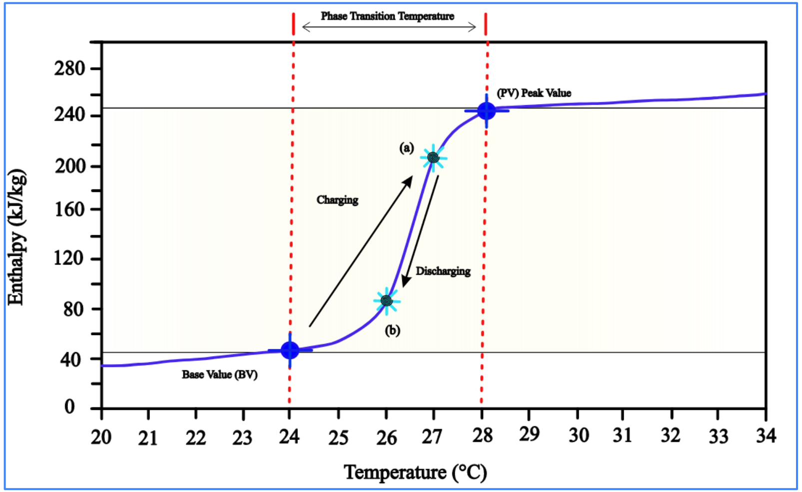
EC_P = Energy consumption after incorporating PCM into the building envelope [kWh]

ESR = Energy Saving Ratio [%]

Methodology…

Novel Performance Indicator

- To have a realistic perspective of PCM performance, new performance indicators, energy-charged coefficient (ECC), and energy discharged coefficient (EDC) are presented in this research.



$$\text{(3)} \quad \text{Charging Fraction (CF)} = \left(\frac{\mathrm{EC}_{\mathrm{PCM}}}{LC}\right)$$

$$\text{(4)} \quad \text{Discharging Fraction (DF)} = \left(\frac{\mathrm{ED}_{\mathrm{PCM}}}{LC}\right)$$

$$\text{(5)} \quad \text{Charging Time Fraction (CTF)} = \left(\frac{\text{Actual time of Charging}}{\text{12 hours}}\right)$$

$$\text{(6)} \quad \text{Discharging Time Fraction (DTF)} = \left(\frac{\text{Actual time of discharging}}{\text{12 hours}}\right)$$

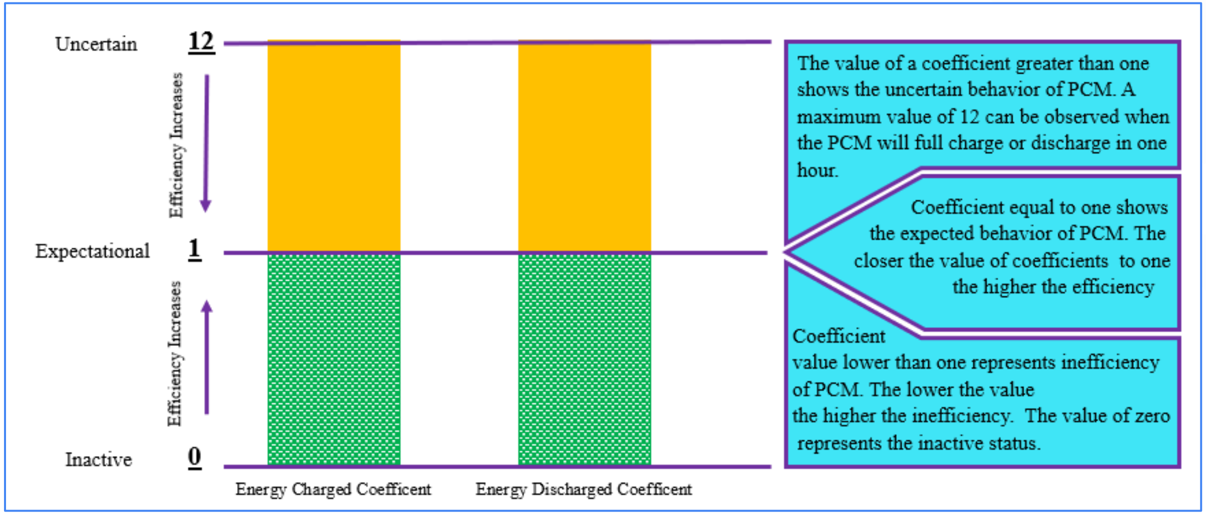
$$\text{(1) Energy Charge (EC)}\ _{PCM} = \text{Enthalpy value at point(a)} - \text{ Base value}$$

$$\text{(2) Energy Discharge (ED)}\ _{PCM} = EC_{pcm} - \text{ Enthalpy value at point(b)}$$

Methodology…

Novel Performance Indicator

- Energy-charged coefficient (ECC), and Energy discharged coefficient (EDC)



The value of a coefficient greater than one shows the uncertain behavior of PCM. A maximum value of 12 can be observed when the PCM will full charge or discharge in one hour.

Coefficient equal to one shows the expected behavior of PCM. The closer the value of coefficients to one the higher the efficiency

Coefficient value lower than one represents inefficiency of PCM. The lower the value the higher the inefficiency. The value of zero represents the inactive status.

$$\text{ECC} = \left(\frac{\text{Charging Fraction}}{\text{Charging Time fraction}}\right)$$

$$\text{EDC} = \left(\frac{\text{Disharging Fraction}}{\text{Discharging Time fraction}}\right)$$

- The closer the value of ECC and EDC to one, the better the PCM performance is during an individual cycle.

Result and Discussion

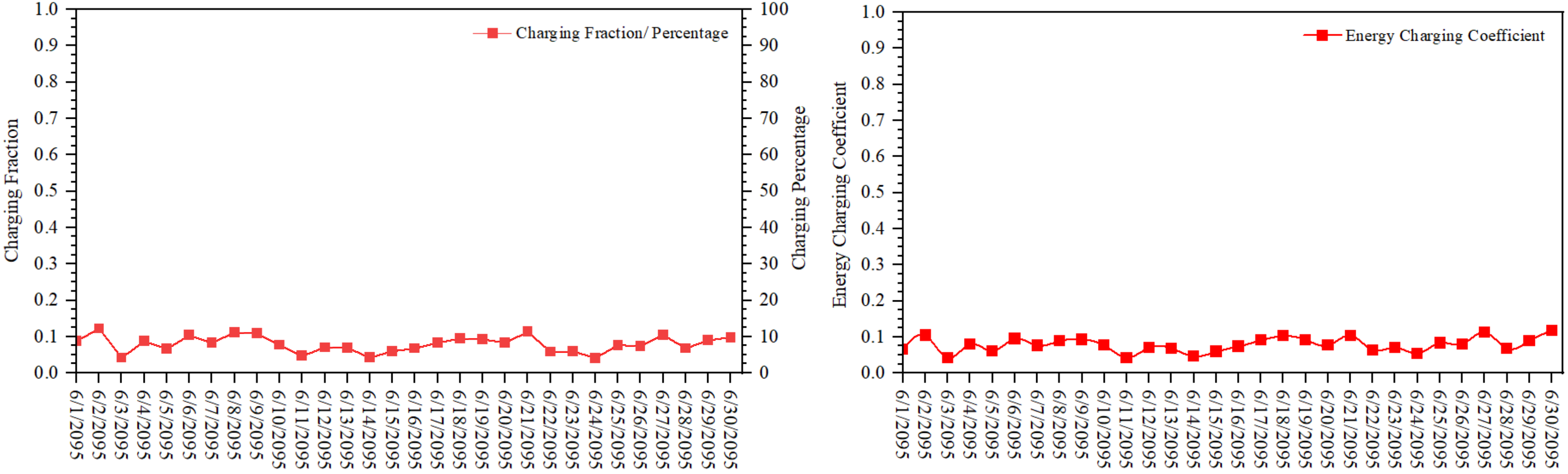
- **Energy saving with PCM under Control condition**

		Boundary condition 1 (b1)			
		B1-SRef	B1-SPCM		
Zone	City	CED [kWh]	Opt- PCM	CES [kWh]	ESR %
Am	Yangon	124835	PCM27	3108	2.5
	Douala	118151	PCM28	2753	2.3
	Hong-Kong	128859	PCM28	3514	2.7
Aw	Bangalore	94042	PCM28	1876	2.0
	Addis-Ababa	60641	PCM28	754	1.2
	Miguel Hidalgo	92531	PCM28	2351	2.5
Af	Kuala Lumpur	128240	PCM28	3251	2.5
	Singapore	129732	PCM28	3505	2.7
	Georgetown	117828	PCM28	3031	2.6
BSk	Kokshetay	84234	PCM27	1999	2.4
	Pavlodar	95225	PCM27	2243	2.4
	Aktobe	77920	PCM27	1473	1.9
BSh	Lahore	173554	PCM28	6814	3.9
	Monterrey	130859	PCM28	4076	3.1
	Jodhpur	153416	PCM28	5300	3.5
Bwh	Medina	146810	PCM28	5542	3.8
	Makkah	169722	PCM28	6321	3.7
	Biskra	147729	PCM28	5458	3.7

		Boundary condition 1 (b1)			
		B1-SRef	B1-SPCM		
Zone	City	CED [kWh]	Opt- PCM	CES [kWh]	ESR %
BWk	Atyrau	91984	PCM27	2328	2.5
	Turkestan	121376	PCM28	3973	3.3
	Kazalinsk	79768	PCM27	1701	2.1
Cfa	Wuhan	161723	PCM28	7240	4.5
	Paris	59939	PCM27	729	1.2
	Srinagar	59998	PCM27	907	1.5
Cfb	Stockholm	48485	PCM28	161	0.3
	London	53866	PCM28	435	0.8
	Bogota	54820	PCM28	521	0.9
Csa	Gaziantep	115691	PCM28	3933	3.4
	Kermanshah	113869	PCM28	4018	3.5
	Lisboa	87581	PCM27	2117	2.4
Cwa	Kathmandu	69133	PCM27	1214	1.8
	Kunming	78094	PCM27	1555	2.0
	Nanning	165711	PCM28	6520	3.9
Dfa	Moscow	54913	PCM30	372	0.7
	Ottawa	87681	PCM28	1857	2.1
	St-Petersburg	44755	PCM30	21	0.0
Dfb	Helsinki	52153	PCM28	257	0.5
	Arhangelsk	35829	PCM30	-178	-0.5
	Umea	45089	PCM30	-3	0.0

Result and Discusssion

- PCM performance in Addis-Ababa.



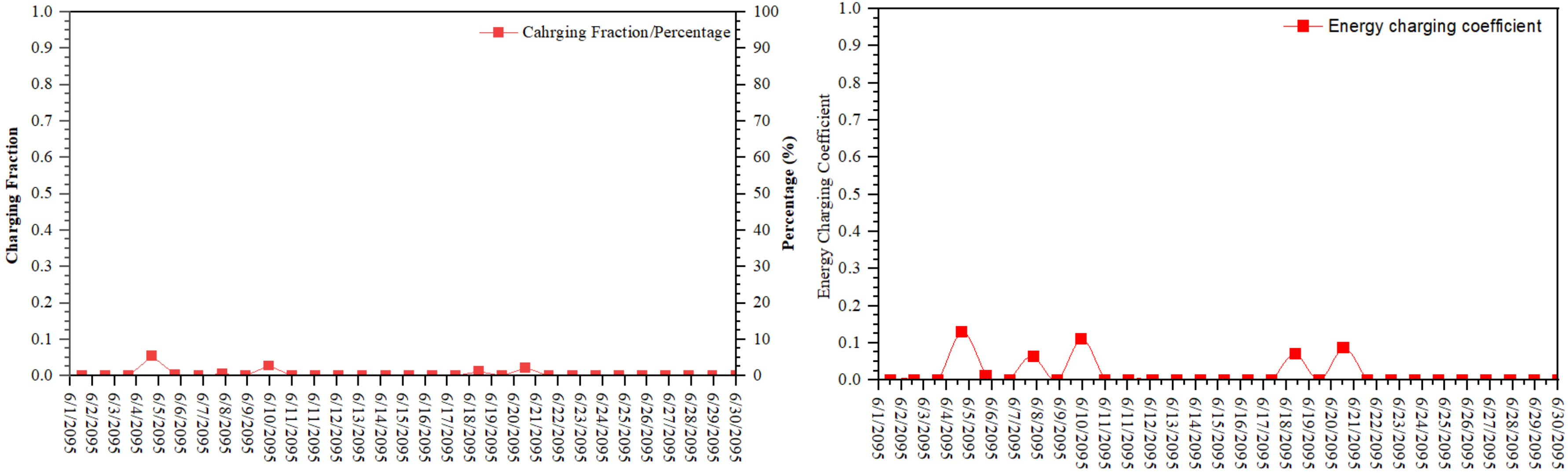
(a)

(b)

Fig. 10. (a) Charging fraction and (b) Energy charging coefficient of PCM28 for the month of June in Addis-Ababa.

Result and Discusssion

- PCM performance in Arkhangelsk.



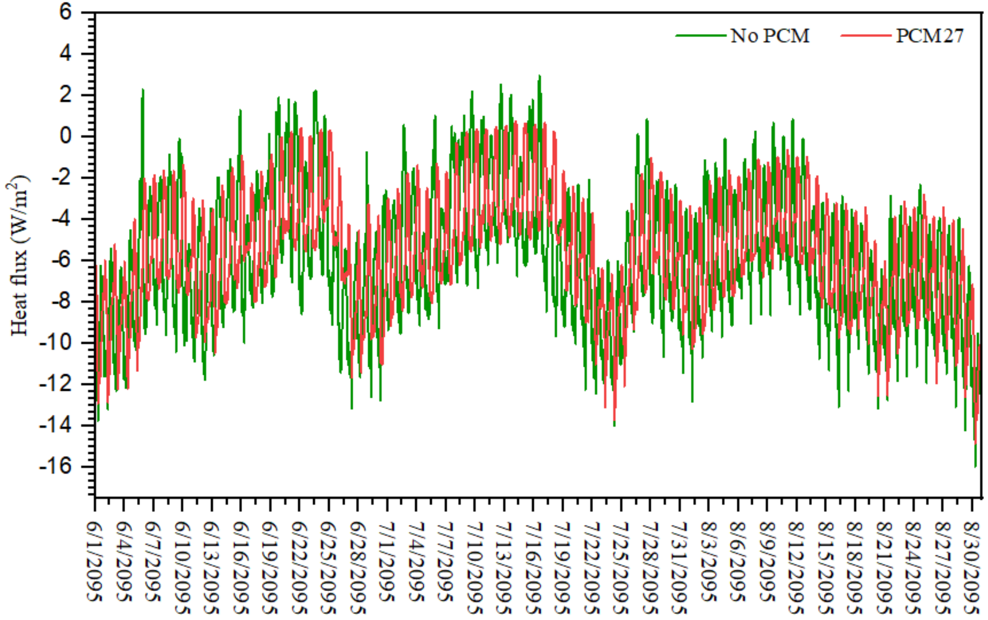
(a)

(b)

Fig. 11. (a) Charging fraction and (b) Energy charging coefficient of PCM30 for the month of June in Arkhangelsk

Result and Discussion

- Why PCM doesn’t perfume in Mild climates under control conditions?



- Inactive PCM in the wall increases thermal inertia and creates a heat trap by reducing the heat flow.

- The trapped heat creates an overheating condition and increases the indoor temperature.

Fig. 12. Heat flux through the south face wall of Stockholm during the summer.

Result and Discussion

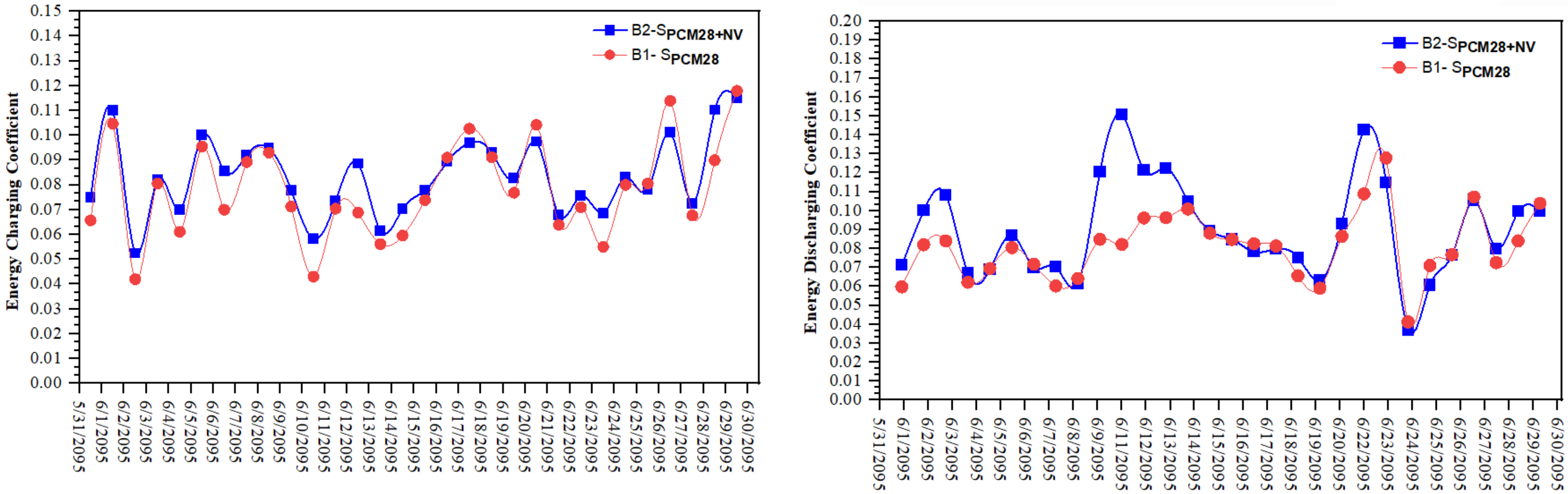
• Energy saving with Night Ventilation and PCM.

		Boundary condition 2 (b2)			
		B2-SNV	B2-SNV+PCM		
Zone	City	CED [kWh]	Opt- PCM	CES [kWh]	ESR %
Am	Yangon	80778	PCM30	773	1.0
	Douala	78016	PCM27	736	0.9
	Hong-Kong	87558	PCM28	1236	1.4
Aw	Bangalore	62006	PCM27	1292	2.1
	Addis-Ababa	39709	PCM28	1572	4.0
	Miguel Hidalgo	65399	PCM27	2472	3.8
Af	Kuala Lumpur	89462	PCM31	849	0.9
	Singapore	88070	PCM28	962	1.1
	Georgetown	79778	PCM28	1222	1.5
BSk	Kokshetay	65266	PCM28	1864	2.9
	Pavlodar	75552	PCM29	1683	2.2
	Aktobe	59999	PCM28	1598	2.7
BSh	Lahore	138651	PCM30	2135	1.5
	Monterrey	97558	PCM31	1295	1.3
	Jodhpur	115011	PCM31	1265	1.1
Bwh	Medina	131384	PCM30	1638	1.2
	Makkah	139022	PCM30	2440	1.8
	Biskra	130287	PCM30	1244	1.0

		Boundary condition 2 (b2)			
		B2-SNV	B2-SNV+PCM		
Zone	City	CED [kWh]	Opt- PCM	CES [kWh]	ESR %
BWk	Atyrau	71177	PCM27	1699	2.4
	Turkestan	104447	PCM29	1498	1.4
	Kazalinsk	62985	PCM28	1647	2.6
Cfa	Wuhan	124014	PCM29	2291	1.8
	Paris	41436	PCM26	1872	4.5
	Srinagar	43015	PCM26	2061	4.8
Cfb	Stockholm	32594	PCM25	1795	5.5
	London	35340	PCM25	2125	6.0
	Bogota	35128	PCM26	1942	5.5
Csa	Gaziantep	95226	PCM29	2490	2.6
	Kermanshah	97238	PCM29	2229	2.3
	Lisboa	63367	PCM27	1910	3.0
Cwa	Kathmandu	45656	PCM26	1771	3.9
	Kunming	50136	PCM27	2018	4.0
	Nanning	123433	PCM29	2239	1.8
Dfa	Moscow	41844	PCM28	1060	2.5
	Ottawa	63717	PCM28	1636	2.6
	St-Petersburg	31642	PCM28	1172	3.7
Dfb	Helsinki	35456	PCM25	1745	4.9
	Arhangelsk	24924	PCM24	1973	7.9
	Umea	33229	PCM26	1433	4.3

Result and Discussion

- PCM performance enhancement in Addis-Ababa with free night ventilation.



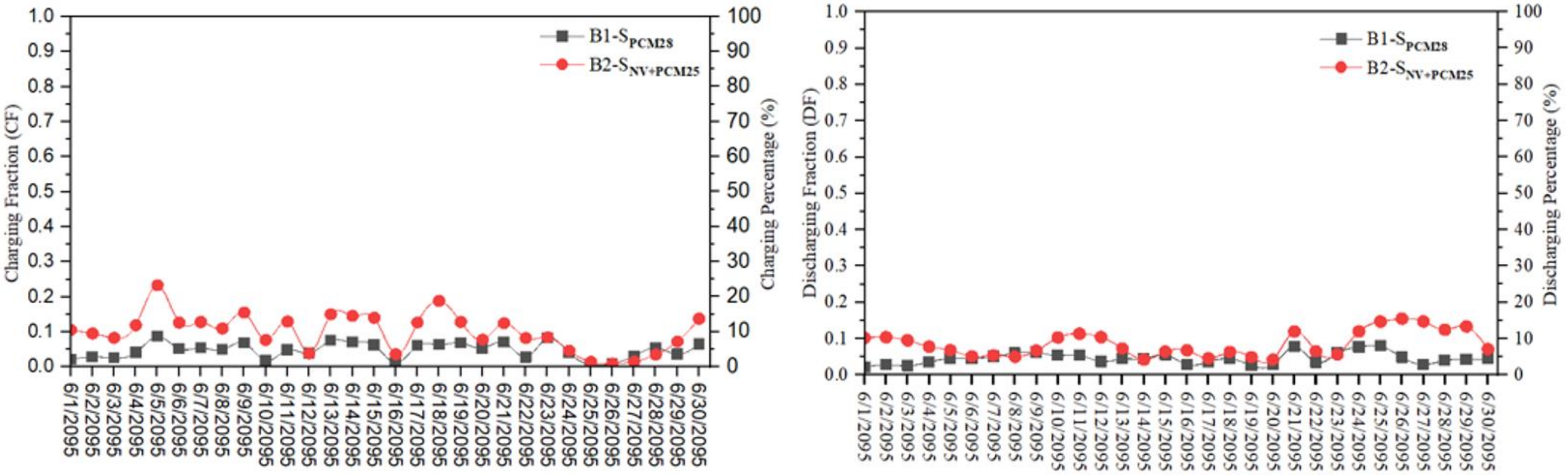
(a)

(b)

Fig. 13. (a)Charging coefficient and (b) Discharging coefficient of PCM28 for the month of June in Addis-Ababa.

Result and Discussion

- PCM performance enhancement in Stockholm with free night ventilation.



(a)

(b)

Fig. 14. Energy charging and discharging fraction of optimum PCM in case of B1-SPCM28 and B2 SNV+PCM25 in Stockholm .

Result and Discussion

- **Energy saving with Changeover Ventilation and PCM**

		Boundary Condition 3 (b3)			
		B3-SCV	B3-SCV+PCM		
Zone	City	CED [kWh]	Opt- PCM	CES [kWh]	ESR%
Am	Yangon	83561	PCM27	2006	2.4
	Douala	80190	PCM29	851	1.1
	Hong-Kong	86196	PCM28	906	1.1
Aw	Bangalore	68685	PCM23	170	0.2
	Addis-Ababa	20681	PCM25	2900	14.0
	Miguel Hidalgo	67900	PCM23	294	0.4
Af	Kuala Lumpur	89773	PCM27	1168	1.3
	Singapore	88373	PCM26	1083	1.2
	Georgetown	83494	PCM29	1076	1.3
BSk	Kokshetay	60539	PCM26	2077	3.4
	Pavlodar	71852	PCM26	1647	2.3
	Aktobe	52602	PCM26	1583	3.0
BSh	Lahore	123413	PCM28	2257	1.8
	Monterrey	98537	PCM28	1886	1.9
	Jodhpur	109596	PCM28	2166	2.0
Bwh	Medina	119518	PCM29	3107	2.6
	Makkah	126084	PCM29	2772	2.2
	Biskra	118805	PCM30	2482	2.1

		Boundary Condition 3 (b3)			
		B3-SCV	B3-SCV+PCM		
Zone	City	CED [kWh]	Opt- PCM	CES [kWh]	ESR%
BWk	Atyrau	71817	PCM27	1532	2.1
	Turkestan	103109	PCM30	1845	1.8
	Kazalinsk	58298	PCM26	1402	2.4
Cfa	Wuhan	108919	PCM29	1844	1.7
	Paris	23496	PCM26	2036	8.7
	Srinagar	30078	PCM25	2530	8.4
Cfb	Stockholm	4640	PCM25	2150	46.3
	London	6514	PCM25	2408	37.0
	Bogota	1556	PCM25	1202	77.2
Csa	Gaziantep	96126	PCM28	1755	1.8
	Kermanshah	98815	PCM30	2159	2.2
	Lisboa	62507	PCM25	1010	1.6
Cwa	Kathmandu	41251	PCM26	506	1.2
	Kunming	43440	PCM25	1805	4.2
	Nanning	109168	PCM29	1633	1.5
Dfa	Moscow	26349	PCM25	1200	4.6
	Ottawa	57726	PCM26	1288	2.2
	St-Petersburg	6020	PCM25	2269	37.7
Dfb	Helsinki	7574	PCM26	1107	14.6
	Arhangelsk	6000	PCM24	900	15.0
	Umea	3313	PCM25	737	18.2

Result and Discussion

- PCM performance enhancement in Stockholm with changeover ventilation .

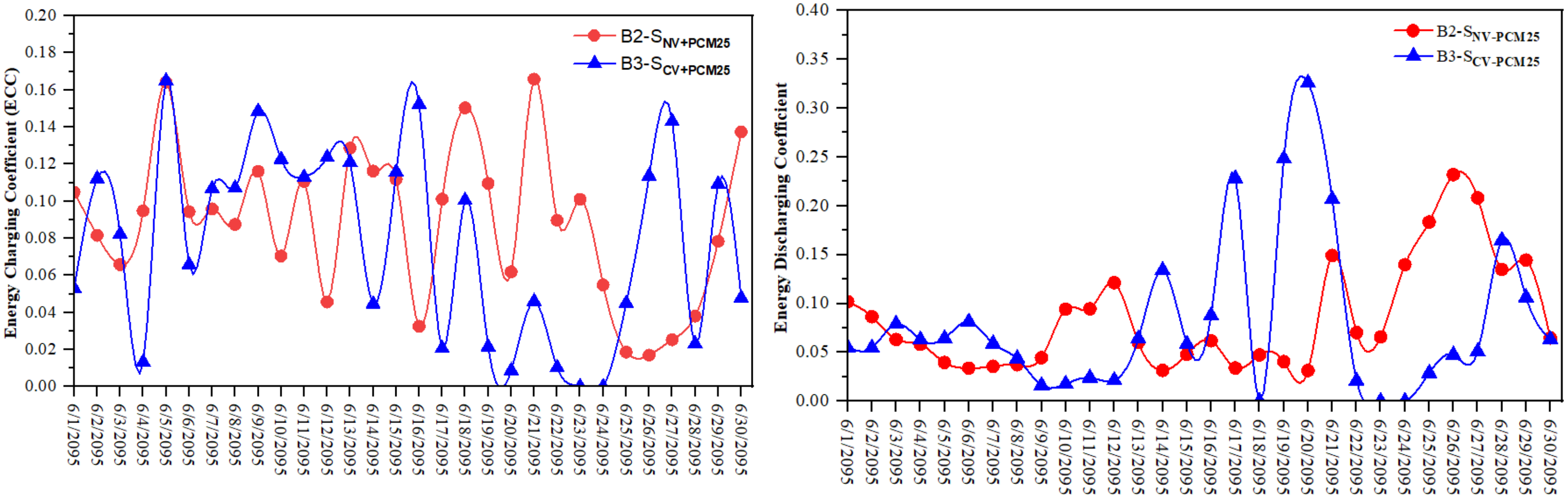
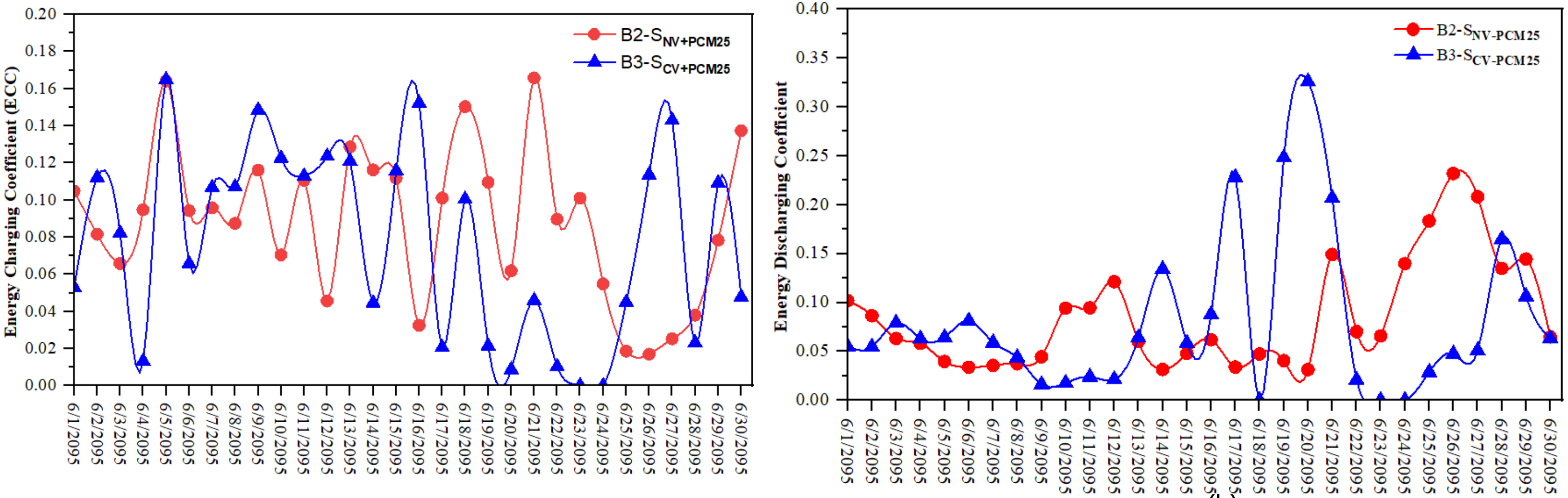


Fig. 15. Energy charged coefficient and Energy discharged coefficient of PCM25 in case of B2-SNV+PCM and B3-SCV+PCM in Stockholm.

Result and Discussion

- PCM performance enhancement in Stockholm with changeover ventilation .



(a) (b)

Fig. 16. Energy charged coefficient and Energy discharged coefficient of PCM25 in case of B2-SNV+PCM and B3-SCV+PCM in Stockholm.

Result and Discussion

- **Establishing the Best Energy saving strategy**

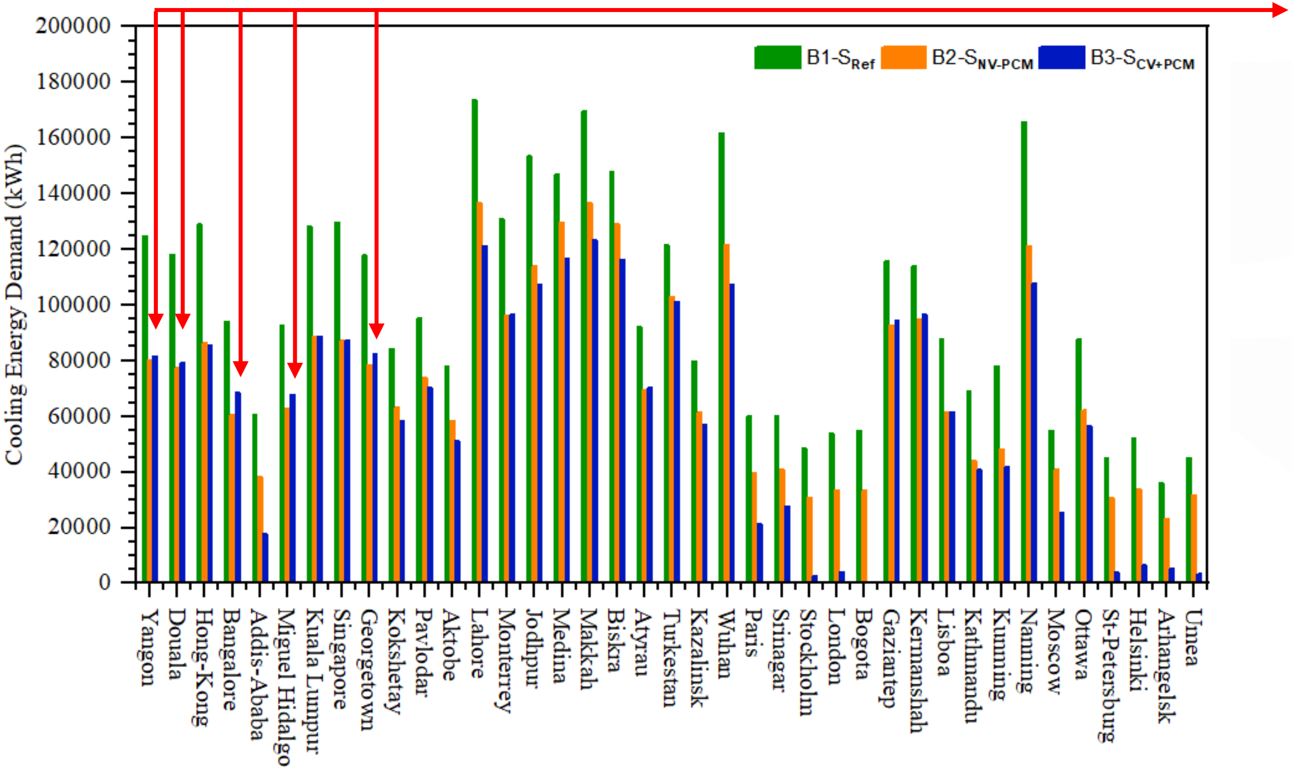


Fig. 17. Comparison of cooling energy demand in B1-S$_{Ref}$, B2-S$_{NV+PCM}$ and B3-S$_{CV+PCM}$ cases.

- Cooling Energy Demand is higher in case of changeover ventilation (CV) and PCM combination

- Most of the cities' changeover ventilation and PCM combination yields maximum cooling energy saving.

Conclusion

- When the HVAC is operational for 24 hours (controlled condition) the optimum PCM performs effectively in all the zones and results in higher cooling energy savings (from 1214 kWh to 7240 kWh) except in the climate condition where the summer is moderate. Thus, the PCM integration is unfavorable under the controlled scenario in these climate regions.

- The implementation of free NV is more favorable in Cwa, Cfb,Dfa, and Dfb zones where the diurnal temperature fluctuation is high, resulting in better recharging of PCM.

- Changeover ventilation implements offer optimized window operation without disturbing indoor thermal comfort and leads to substantial CES in all climate zones. The integration of PCM with changeover ventilation further enhances the cooling energy saving (506 kWh to 2772 kWh) in all climate zones.

- In comparison to the controlled case and free night ventilation case the combination of PCM and changeover offers maximum savings and turns out to be the best strategy for cooling energy saving.

- Overall, this study strengthens the idea of implementing energy efficiency technology in the future by evaluating the potential of PCM for cooling energy savings with climate change. The finding can be used as a guideline for energy-efficient building design in the future.

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