

Energy flexibility of PCM-configured envelopes under Hong Kong time-of-use tariffs: a parametric simulation[#]

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ABSTRACT

Buildings in warm-humid climates exhibit pronounced midday cooling peaks, which makes demand-side flexibility under time-of-use tariffs especially valuable. Phase change materials configured in the envelope of walls and roofs can provide latent storage, yet performance under realistic tariffs with explicit hysteresis remains under-quantified. This study develops a reproducible, tariff-linked workflow that couples EnergyPlus with a hysteresis-consistent PCM model and automates a jEPlus parametric sweep. A medium-office archetype in Hong Kong is simulated under a representative four-block tariff, testing overnight pre-cooling to 22 to 24 °C and midday set-point relaxation to 24.5 to 25 °C, with the PCM melting range aligned to the cooling band. Performance is evaluated using the flexibility factor, on-peak and off-peak energy shifting, peak load moderation and tariff-based cost. The combined strategy delivered a 48.7% daily cooling-cost saving relative to the non-PCM baseline, with on-peak cooling energy reduced by 34.3%, off-peak use increased by 131.1%, and on-peak peak cooling load and peak electric demand reduced by 21.3% and 19.7%, respectively. Single-lever strategies yielded smaller gains, and neglecting hysteresis distorted the timing and magnitude of peaks. The results show that material properties and control could be co-designed, and they provide a transferable workflow with decision-ready indicators for PCM-enabled, tariff-responsive design in warm-humid offices.

Keywords: phase change material (PCM) envelope; building energy flexibility; peak demand reduction and load shifting; parametric optimisation.

1. INTRODUCTION

Rapid decarbonisation of the power sector increasingly relies on buildings providing demand-side flexibility by shifting or reshaping consumption to match

real-time system conditions and price signals [1-3]. In warm-humid cities such as Hong Kong, space cooling dominates annual electricity use and midday solar gains coincide with peak occupancy. Under these conditions, time-of-use pricing offers a practical lever to move cooling loads away from the costliest, most carbon-intensive hours. When tariffs split the day into an inexpensive overnight off-peak, a morning shoulder, a punitive midday peak, and an evening period (with an additional demand charge on the midday peak window), the pronounced intraday price differentials create clear incentives to exploit the building fabric as a short-term thermal store [4].

PCMs embedded in building envelopes provide latent thermal storage well-matched to diurnal cycles. By absorbing heat near a chosen melting temperature and releasing it as temperatures fall, they moderate heat flux through the envelope and curb mechanical cooling during expensive periods [5, 6]. The benefits realised depend on aligning the PCM properties and control strategy with the local climate and tariff structure. In warm-humid environments, elevated night-time temperatures and high latent loads can undermine PCM recharging unless off-peak pre-cooling, ventilation, and set-point adjustments are carefully coordinated with the tariff periods. Recent studies have clarified flexibility concepts and performance indicators, showing that control design is critical. Grid-interactive control strategies that adjust supply and set-points in a controlled manner can deliver reliable flexibility at the building scale [1-3, 7], and coordinating the operation of many buildings can amplify system-level gains and alter the apparent value of demand shifting under a given tariff [8, 9].

Despite these advances, three methodological gaps remain for envelope-integrated PCMs in cooling-dominated, humid climates. First, studies focusing on cost and flexibility under realistic time-of-use and

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demand-charge tariffs are still limited. Many investigations report energy or comfort outcomes but do not quantify tariff-linked value using decision-ready indicators [1-3, 7-9]. Second, the fidelity of PCM modelling is uneven. A stable representation of moving latent heat fronts and melt–freeze hysteresis requires a consistent formulation combined with the CondFD solver in EnergyPlus; omitting or over-simplifying hysteresis can bias both the timing and magnitude of predicted peak reduction [10, 11]. Third, reproducible parametric workflows that combine high-fidelity EnergyPlus envelope models with jEPlus automation and multi-period cost calculations are under-documented, limiting transferability across different tariff years and climates [2, 3, 12].

This study addresses these gaps for a small-sized office archetype under a representative four-block Hong Kong tariff. We implement a tariff-aware control framework that combines off-peak pre-cooling during the cheapest tariff window with a modest midday set-point relaxation. The building envelope includes a PCM layer modelled with a hysteresis-consistent EnergyPlus CondFD scheme. A jEPlus parametric sweep was performed over the PCM peak melting temperature (24 °C and 26 °C), latent heat capacity (through an infinite-thermal-conductivity idealization vs finite), PCM layer thickness (fixed at 0.050 m), and control offsets. Performance is evaluated using daily tariff-linked indicators: the flexibility factor, on- and off-peak cooling energy redistribution, reductions in peak cooling load and peak electric demand, and a daily cost breakdown (energy, demand, and rebate components). This integrated, reproducible workflow quantifies value under a realistic tariff with decision-oriented metrics, uses a hysteresis-consistent PCM model to capture charge–discharge timing, and co-tunes material properties with control strategies in a jEPlus framework that can be adapted to other tariff conditions [1-12].

2. METHODS

2.1 Platform and model overview

EnergyPlus was used as the simulation engine. Phase-change behaviour was represented using the Conduction Finite Difference (CondFD) scheme so that latent heat fronts were resolved in both space and time. The PCM was modelled with a hysteresis formulation distinguishing melting and freezing branches with separate transition widths. The workflow was automated using jEPlus.

Geometry, constructions, internal gains, HVAC templates, and control schedules were authored in Design Builder and exported as EnergyPlus input files. jEPlus orchestrated the parametric plan by inserting parameter values into the IDF templates, launching the simulations, and collating the outputs for post-processing.

2.2 Building prototype, climate and simulation frame

The prototype building was a single-storey, low-rise office with one core and four perimeter zones, based on the ANSI/ASHRAE/IES Standard 90.1-2019 Appendix G model [13]. Occupancy, lighting, plug loads, ventilation, and infiltration were set according to the reference model. Hong Kong Typical Meteorological Year climate data were used. The simulation time step was 1 minute. The baseline heat-balance algorithm was the conduction transfer function (CTF), which was switched to CondFD for the PCM cases (see Section 2.3). Each zone was served by a packaged single-zone air-conditioning system with a direct-expansion (DX) cooling coil. Table 1 summarises the key building and environment input parameters, and Table 2 lists the main simulation and HVAC settings.

Table 1 Core building environmental inputs.

Parameter	Value	Notes
Occupancy density	0.0538 persons m⁻²	18.5806 m ² person ⁻¹ .
Lighting power density	10.671 W m⁻²	Office lighting profile.
Receptacle equipment density	6.78 W m⁻²	Weekday office profile.
Design outdoor-air areal flux	4.318×10⁻⁴ m s⁻¹	
Infiltration areal flux	5.6957×10⁻⁴ m s⁻¹	Velocity coefficient 0.224.
Window-to-wall ratio	0.19	

Table 2 Simulation and HVAC settings.

Setting	value	Notes
Time step	1min	60 steps per hour.
Heat-balance algorithm (baseline)	CTF	Changed only for PCM runs.
DX cooling coil COP	3	Auto-sized capacity and flow.

2.3 Envelope configuration and phase-change material

Opaque constructions from the reference model were retained as the host assembly. A PCM layer was added on the innermost side of selected walls and roofs

so that the latent thermal store was closely coupled to the zone air and cooling control. The PCM was represented with the hysteresis model in EnergyPlus, which assigns distinct enthalpy–temperature curves for melting and freezing. The CondFD solver was enabled for all PCM simulations to stably and accurately resolve the moving phase-change front, following EnergyPlus best-practice guidance.

Table 3 PCM factors and levels for the parametric study.

Factor	Levels
Peak melting temperature T_m	26, 24 °C
Layer thickness d	0.050 m

2.4 Four-block tariff adopted for cost and flexibility analysis

A four-block time-of-use tariff structure was adopted, consistent with the schedule used in the results. The blocks were fixed daily time windows (local time) and included an additional peak demand charge as well as a uniform rebate. The tariff parameters are given in Table 4 [14].

Table 4 Study tariff with four price blocks and a demand charge [14].

Symbol	Time window	Energy price	Units
TP ₁	23:00–08:00	0.479	HKD kWh ⁻¹
TP ₂	08:00–12:00	0.675	HKD kWh ⁻¹
TP ₃	12:00–16:00	9.975	HKD kWh ⁻¹
TP ₄	16:00–23:00	0.675	HKD kWh ⁻¹
TP ₅	Peak-demand charge	2.28	HKD kVA ⁻¹
TP _{rb}	Uniform rebate	6	HKD kWh ⁻¹

2.5 Cost model and flexibility indicators

Hourly electricity E_h is taken from simulation outputs in kWh. Binary indicators (h) mark membership of block $j \in \{1,2,3,4\}$. Daily peak apparent demand D_m in kVA is computed from the maximum fifteen-minute average within the midday block, assuming a power factor of 0.9. The daily energy cost is

$$C_{cn} = \sum_{h=1}^{24} E_h (TP_1 I_1(h) + TP_2 I_2(h) + TP_3 I_3(h) + TP_4 I_4(h)) - TP_{rb} \sum_{h=1}^{24} E_h$$

The demand charge is

$$C_{dem} = \sum_{n=1}^{24} TP_5 D_m$$

The total cost is

$$C_{tot} = C_{en} + C_{dem}$$

The flexibility factor (FF) divides the day into a low-penalty off-peak period and a high-penalty on-peak period, and quantifies the load shifting between them. Here FF is defined as the difference between off-peak and on-peak cooling energy, divided by the total daily cooling energy. Specifically, letting the sets of time steps classified as \mathcal{T}_{low} (off-peaks) and \mathcal{T}_{high} (on-peaks) penalty, we calculate the factor is

$$FF = \frac{\int_{\mathcal{T}_{low}} P(t)dt - \int_{\mathcal{T}_{high}} P(t)dt}{\int_{\mathcal{T}_{low}} P(t)dt + \int_{\mathcal{T}_{high}} P(t)dt}$$

2.6 Tariff-aware controls and schedules

Thermostat schedules were defined using four daily periods, with office hours from 07:00 to 18:00. Three control strategies were tested within the comfort band of 22–26 °C operative temperature. Strategy S1 applied overnight pre-cooling during TP₁ with a 0–2 K offset, targeting 22–24 °C before occupancy. Strategy S2 applied a midday set-point relaxation during TP₃ with a 0–1 K offset, raising the cooling set-point to 24–25 °C. Strategy S3 combined S1 and S2. The control windows mirrored the tariff structure to encourage off-peak cooling and to limit rebound in the evening. Fig. 1 illustrates these operational schedules.

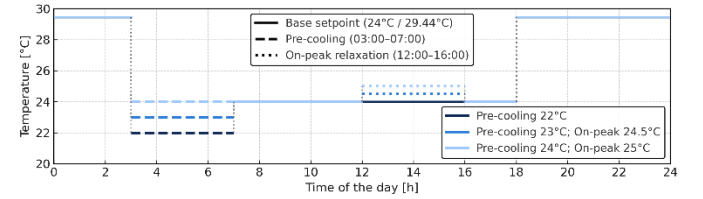


Fig. 1 Operation schedules

2.7 Parametric plan with EnergyPlus and jEPlus indicators

The parametric study was defined by the variables and ranges shown in Tables 3 and 6. The material parameter was the PCM peak melting temperature, at two discrete levels (24 °C and 26 °C) as given in Table 3, with the PCM layer thickness fixed at 0.050 m. The control variables were the overnight pre-cooling offset in TP₁ (0–2 K) and the on-peak relaxation offset in TP₃ (0–1 K), as listed in Table 5.

Table 5 jEPlus design variables and bounds.

Variable	range	Notes
PCM peak melting temperature	24–26 °C	Discrete, Table 3
Pre-cool offset	0–2 K	Overnight window
On-peak relaxation	0.5–1 K	Midday window

An IDF template was prepared with placeholders for the melting temperature and the two control offsets. jEPlus substituted each trial combination of these values, generated the batch run list, launched EnergyPlus, and aggregated the hourly results. The outputs collected included zone air temperature, operative temperature, sensible cooling power, and fan and coil electricity use. A post-processing script then applied the tariff formulas (Section 2.4) and flexibility metrics (Section 2.5) to compute, for each run, the daily bill components, flexibility factor, on- and off-peak energy shifts, and peak reduction metrics. A comfort guard band of 22–26 °C operative temperature was maintained for all cases. All PCM simulations used the CondFD solver with the hysteresis material model, consistent with the modelling choices described above.

3. RESULTS

Across all scenarios, cost reduction was achieved primarily by shifting cooling loads from the expensive midday period to the overnight off-peak period. The combined control strategy produced the lowest daily cost and the highest flexibility factor; the single-lever control strategies performed intermediately, and the baseline had the highest cost. Figures 2–6 show that flexibility factor generally increases with cost savings, that the energy-charge component accounts for most of the bill reduction, and that the scenarios are clearly ranked by total cost. Figures 7–13 confirm a substantial reduction in on-peak cooling coupled with a corresponding increase off-peak, alongside improvements in peak demand metrics. (Unless otherwise stated, percentages refer to absolute changes, i.e. percentage-point differences, relative to the baseline.) All scenarios remained within the comfort band of 22–26 °C operative temperature.

3.1 Flexibility factor and daily cost saving

There was a strong correspondence between flexibility factor and daily cost. The baseline case yielded $FF = -0.360$ with a daily cost of 510.2 HKD. By contrast, the best combined scenario (pre-cooling to 22 °C from 03:00–07:00 and midday set-point relaxation to 25 °C from 12:00–16:00, using a PCM with an aligned melting range) achieved $FF = 0.247$ and a daily cost of 261.8 HKD, corresponding to a 48.7% cost savings.

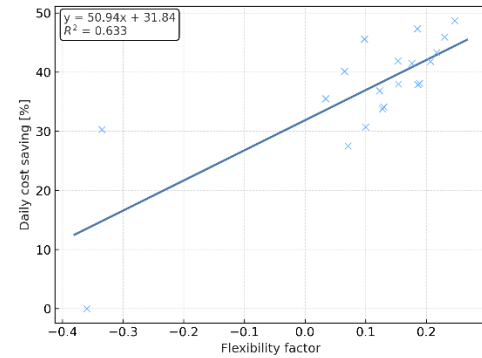


Fig. 2 Flexibility factor vs cost saving rate.

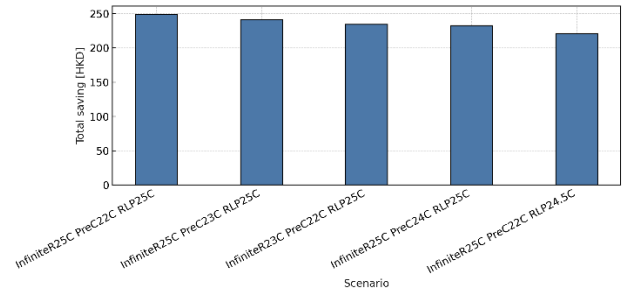


Fig. 3 Contributors to daily cost saving.

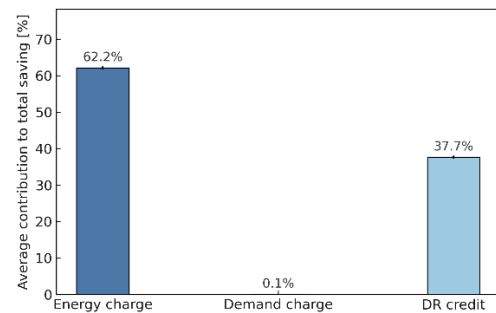


Fig. 4 Average composition of savings.

A strong monotonic relationship was observed between flexibility and cost savings (Fig. 2), with $R^2 = 0.633$ and a fitted line of $y = 50.94x + 31.84$. An increase of 0.10 in FF corresponded to approximately 5.1% additional cost savings. The breakdown of savings in Figs. 3 and 4 indicates that the energy charge contributes the majority of the cost reduction, the demand-response rebate provides a smaller share, and the demand charge reduction is minimal under these tariff rates. Figure 5 ranks the scenarios by total cost, and Fig. 6 compares the mean outcomes for each scenario set; both confirm the superiority of the combined strategy over the single-lever and PCM-only cases. The close alignment between flexibility factor and tariff-based savings supports the use of reproducible, time-resolved performance indicators to evaluate operational value and to aggregate scenario performance [1, 2].

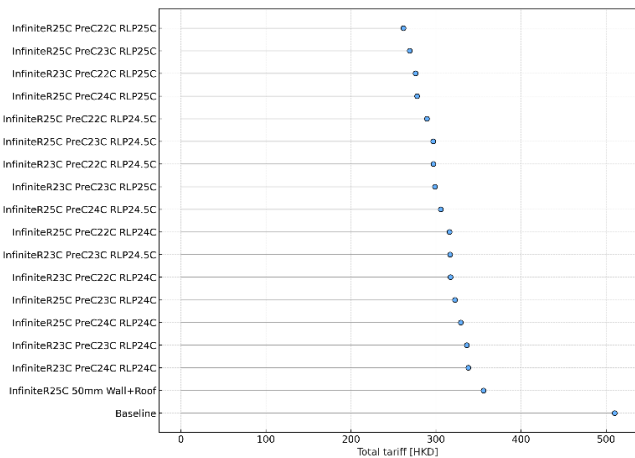


Fig. 5 Ranking of scenarios by total cost.

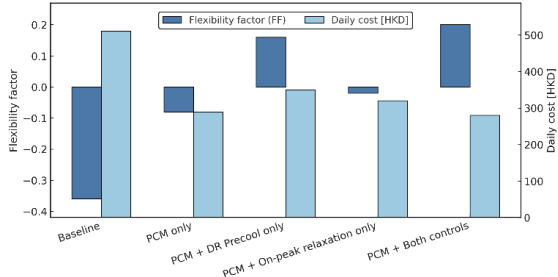


Fig. 6 Flexibility factor vs daily cost (set means).

3.2 Cooling load shifting and peak-demand reduction

The tariff-aware control strategies substantially redistributed cooling loads and moderated peak demands. Compared to the baseline, the best combined case reduced on-peak cooling energy by 34.3% and increased off-peak cooling energy by 131.1% (Fig. 7). It also achieved a 21.3% reduction in peak cooling load and a 19.7% reduction in peak electric demand during the on-peak period (Fig. 8).

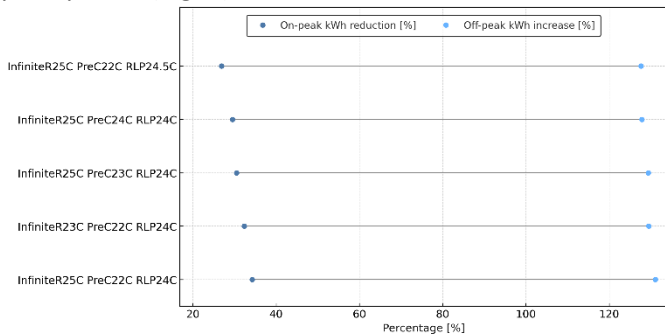


Fig. 7 Load shifting (top 5 scenarios).

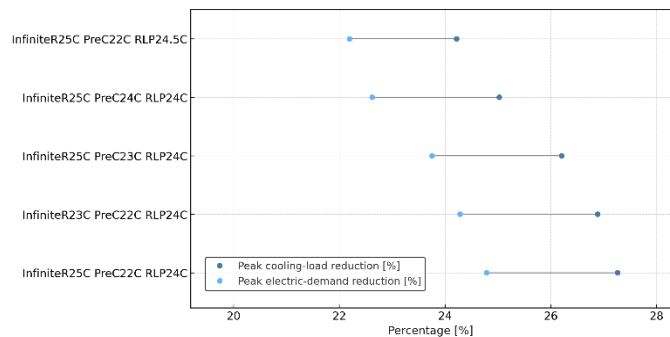


Fig. 8 Peak Reduction (Best 5 scenarios).

Fig. 9 shows an almost linear relation between on-peak cooling-energy reduction and daily cost saving ($R^2 = 0.989$; slope 1.40), so each 1% reduction in on-peak cooling energy yields about 1.4% additional saving. Flexibility is also linked to peak moderation, though with greater scatter: Figure 10 reports $R^2 = 0.350$ between peak cooling-load reduction and the flexibility factor, where a 0.10 increase in the factor corresponds to about 2.2% further peak-load reduction. Fig. 11 contrasts the best scenario with the baseline across all indicators. Fig. 12 and Fig. 13 show the intervention hierarchy: PCM-only gives limited shifting; single-lever pre-cooling or set-point relaxation improves timing; the combined strategy delivers the most balanced shift and the largest economic benefit. In summary, correctly timed pre-cooling and midday relaxation, together with a PCM melting range aligned to the occupied cooling band, are required to achieve load shifting and peak reduction in a stable, repeatable manner.

These findings are consistent with previous studies showing that accurately modelling PCM hysteresis is necessary to predict the timing and magnitude of peak load relief, and that supervisory or feedback control is required to activate thermal storage at the optimal times [7, 10].

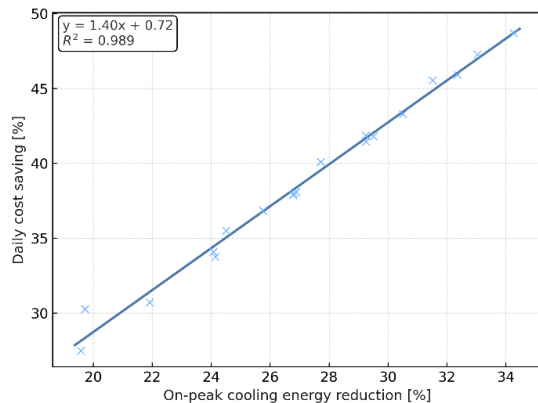


Fig. 9 Cost saving vs on-peak energy reduction.

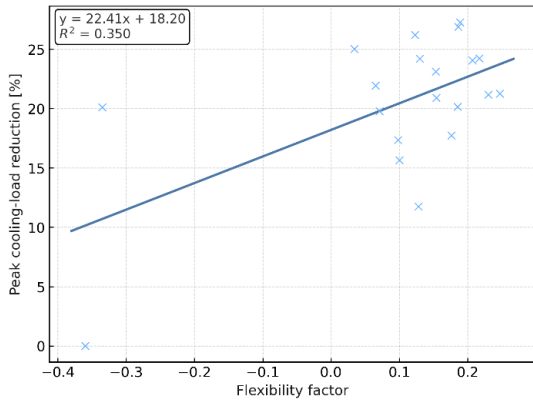


Fig. 10 Peak cooling-load reduction vs flexibility factor.

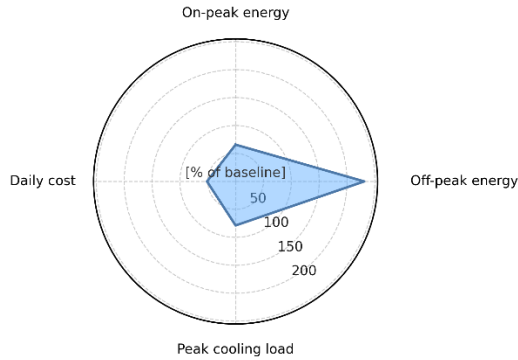


Fig. 11 Best scenario vs baseline.

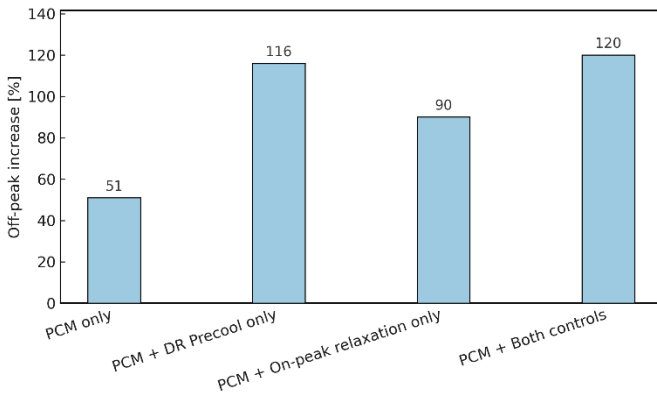


Fig. 12 Off-peak increase across scenarios(means).

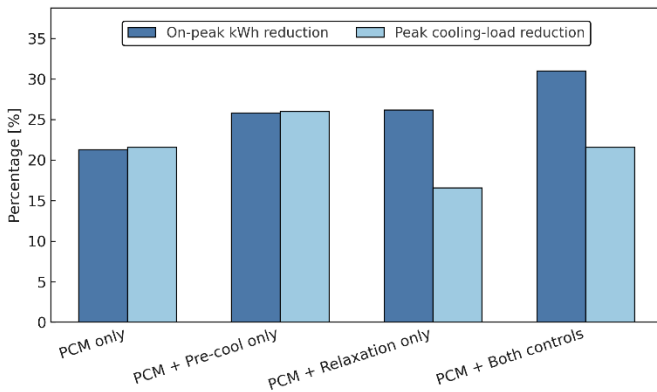


Fig. 13 Load shifting and peak reduction (typical scenarios).

4. DISCUSSIONS

The results confirm a central proposition in the flexibility literature that value is governed by timing. Under a realistic four-block tariff, the configuration that pre-cools in the early morning to 22 °C, relaxes the midday set-point to 25 °C, and uses a PCM melting band of 24–26 °C with hysteresis shifts cooling from punitive to inexpensive periods and delivers the largest gains in both cost and peak moderation. This mechanism-centred view accords with recent syntheses that formalise indicators and aggregation methods for building energy flexibility and show that well-timed, tariff-aware responses at portfolio scale yield substantial system benefits [1-3, 12].

Two methodological elements explain the magnitude and repeatability of benefits in warm-humid conditions. First, material-control co-ordination places the PCM melting band inside the occupied comfort range so that charge and release occur when they are operationally useful within the tariff windows. Secondly, hysteresis-consistent modelling with CondFD is required to capture phase-change timing and to avoid overstating peak relief, which can occur with simplified or non-hysteretic representations [10, 11]. Embedding these choices in a reproducible EnergyPlus-jEPlus workflow with tariff-linked indicators shifts the analysis from generic energy savings to operational value under real pricing, and complements recent analytical and probabilistic formulations of flexibility quantification [1-3, 12].

Implications for building design and operation are direct. The envelope should be treated as a latent thermal battery. Designers should specify PCM layers aligned with the operative temperature band, and commission time-aware BMS schedules that pre-cool in the cheapest window and adopt a modest midday relaxation. In practice, this recipe preserves comfort, is straightforward to implement, and yields decision-ready evidence through flexibility and peak-reduction metrics. Standards and policy should recognise flexibility alongside efficiency through credits for fabric-integrated storage, reference to peak-reduction and on- versus off-peak redistribution in compliance paths, and incentives aligned with verifiable peak shaving and off-peak utilisation [1, 2, 12].

The workflow generalises with targeted retuning. In continental or dry-hot climates, larger diurnal swings and night ventilation or radiative cooling favour re-solidification and ease overnight recharge, while tropical climates typically require deliberate pre-cool to avoid under-charging and loss of flexibility. Under real-time or

critical-peak pricing, the same framework can host predictive or supervisory control to target transient spikes, consistent with recent demonstrations of grid-interactive control and multi-building co-ordination that amplify benefits when timing is well managed [7-9, 14, 15].

5. CONCLUSIONS

This parametric investigation shows that tariff-aware control co-designed with a PCM-enhanced envelope unlocks substantial and repeatable demand-side flexibility in a warm-humid office. The best configuration reduced daily cooling cost by 48.7%, decreased on-peak cooling energy by 34.3%, increased off-peak usage by 131.1%, and lowered on-peak peak cooling load and peak electric demand by approximately 20%. The mechanism is temporal shifting enabled by latent storage, and hysteresis-consistent modelling ensures credible charge and discharge timing.

Methodologically, the study provides a reproducible workflow that links high-fidelity PCM simulation and CondFD with jEPlus automation and tariff-linked, decision-ready indicators. The approach is transferable to other building types, climates and tariff designs through straightforward retuning of PCM melting temperature and control windows. Practically, the prescription is to treat the envelope as a thermal battery and to co-design materials and controls around the tariff so that buildings deliver lower peaks, greater off-peak absorption and smoother renewable integration, with clear routes to integration in design practice, operator guidance and future performance standards.

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