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Net-Zero energy strategies for tropical hotels using passive design and PCM-Based envelope systems

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ABSTRACT

Motivated by the advancement of the net-zero hospitality concept in Indonesia, and considering the relatively high average humidity levels found in tropical countries with varied climatic conditions, this study examines the effects of integrating phase change materials (PCMs) into hotel building envelope systems across six Indonesian cities representing a wide range of tropical climate classifications (Af, Am, Aw, and Bsh). The objective is to improve total energy consumption (TEC), life cycle cost (LCC), and carbon dioxide (CO_2) emissions performance. This research evaluates the efficiency of PCM-reinforced wall systems under two dual-objective optimization scenarios: (1) TEC versus LCC and (2) TEC versus CO_2 emissions, using an integrated simulation framework combining DesignBuilder, EnergyPlus, and a multi-objective genetic algorithm (NSGA-II). The results indicate that PCM integration can substantially enhance total energy savings and reduce CO_2 emissions by up to 47.80 percent and 52.96 percent, respectively, particularly in earth-based and masonry wall assemblies. Significant economic benefits were also identified, with life cycle cost savings reaching up to 29.62 percent and reductions in the average tariff cost per square meter of approximately 22.15 percent in high-tariff zones, such as Denpasar, when these construction systems are applied. The optimal PCM configurations were found to be climate-dependent, performing most effectively with external PCM placement and melting temperature ranges between 23 and 29°C. Overall, the findings demonstrate that PCM integration can provide sustainable, cost-effective, and climate-responsive building envelope solutions for the hospitality sector in tropical regions. Furthermore, the study presents a robust optimization framework that is scalable for both retrofit applications and new construction, supporting Indonesia's ecotourism development and zero-emission building agenda.

Introduction

In response to the global pursuit of sustainable design and carbon-neutral development, increasing pressure has been placed on the building sector to conceive and implement energy-efficient design strategies. Existing buildings account for more than 40 percent of global energy consumption and are responsible for nearly 35 percent of total greenhouse gas emissions (Lu and Lai 2019). Within this context, hotel buildings present a particular challenge in terms of energy demand, especially in warm and tropical climates, due to their continuous operation, high internal load densities, and elevated thermal comfort requirements. These conditions are further intensified in hot and humid regions such as Indonesia, where tropical climates increase operational energy costs and significantly contribute to environmental degradation (Nasrullah and Hamdy 2024; Nasrullah et al. 2024).

Hotel buildings differ substantially from residential and conventional commercial buildings with respect to occupancy patterns, internal heat gains, lighting loads, and occupant expectations. Guests typically expect stable indoor thermal conditions regardless of external climatic variations, whether hot or cold, which results in HVAC systems operating for extended periods. Consequently, hotels rank among the most energy-intensive building types on a per-square-meter basis. Therefore, identifying effective strategies to reduce energy consumption in hotel facilities without compromising occupant comfort has become a critical energy and climate policy objective, particularly in Southeast Asian countries, where tourism growth is rapid and urban development is accelerating.

Within this framework, the building envelope functions as the thermal interface between exterior and interior environments and plays a crucial role in limiting energy losses while enhancing passive thermal performance. A well-designed building envelope can significantly reduce heating and cooling demands by minimizing unwanted heat gains and losses, thereby supporting sustainable building operation and lowering maintenance costs. In hot climates, where cooling loads dominate, envelope design strategies must be specifically adapted to resist high external heat gains and protect interior spaces from pronounced temperature fluctuations.

Phase Change Materials (PCMs) have attracted considerable attention for their potential application in thermal energy storage, as their capacity to regulate indoor temperatures offers significant promise as a strategy for enhancing building energy efficiency and achieving net-zero energy targets, particularly when incorporated into wall systems of buildings exposed to high thermal loads. In addition to walls, PCMs have also been applied in roofs, ceilings, and floor assemblies to improve thermal performance (BioPCM 2023).

Furthermore, Wang et al. (2020) identified wall orientation as a critical factor influencing PCM effectiveness, while Li et al. (2021) emphasized that PCM melting temperatures must be carefully aligned with localized thermal load conditions. Wi, Chang, and Kim (2020) evaluated phase-stabilized materials (PSMs) in South Korea and reported an average annual energy reduction of approximately 5 percent, attributed to enhanced thermal buffering capacity. Collectively, these findings confirm the effectiveness of PCM-integrated design as a passive energy strategy for buildings subjected to high thermal loads.

Despite the extensive body of literature demonstrating the energy-saving potential of PCMs, most previous studies have focused primarily on residential or office buildings, leaving hotel buildings relatively underexplored. Moreover, many investigations rely on short-term performance comparisons, such as daily or seasonal assessments, without adequately addressing long-term behavior or climatic variability, particularly within tropical regions. This lack of longitudinal research related to hotel buildings represents a significant knowledge gap, especially in countries where tourism plays a vital economic role, including Indonesia, where energy-intensive hotel operations pose substantial environmental challenges (Arivazhagan et al. 2025; Skovajsa et al. 2022; Hakim, Edriawan, and Putra 2024; Byrne et al. 2019).

This study proposes a novel simulation-based multi-objective optimization framework for integrating PCM-enhanced passive envelope systems in hotel buildings located in tropical climatic zones of Indonesia, with specific emphasis on varying hot-humid regional conditions. The proposed methodology employs advanced computational techniques to explore a broad range of PCM configurations aimed at achieving energy savings, reducing life cycle costs, and minimizing CO_2 emissions, which are defined as key performance objectives in the pursuit of net-zero energy hotel buildings (Byrne et al. 2019; G. Wang et al. 2023; Zhang et al. 2022; Wei et al. 2022).

The study utilizes a nondominated sorting genetic algorithm (NSGA-II), a robust evolutionary optimization method, in conjunction with EnergyPlus, a validated building energy simulation engine. The parametric framework enables detailed analysis of PCM-related design variables, including melting temperature, layer thickness, and placement within wall assemblies. Multi-objective optimization is applied to systematically investigate trade-offs among energy efficiency, environmental performance, and economic feasibility (Saffari et al. 2017; Tabares-Velasco, Christensen, and Bianchi 2012; Beltran, Martínez-Gómez, and Lobato-Cordero 2017).

The commercially available PCMs selected for this investigation include a bio-based material, BioPCM (BioPCM 2023), characterized by an adjustable melting temperature range, and a higher-performance material, InfiniteR PCM (BioPCM 2024), noted for its thermodynamic stability under tropical climatic conditions. These PCMs are incorporated into several wall typologies commonly used in Southeast Asian hotel construction, including brick masonry, concrete block walls, cast-in-place concrete, and earthen wall systems. The selected wall configurations reflect their widespread adoption in both conventional and contemporary hotel developments in Indonesia and neighboring regions (Yun et al. 2020).

The simulation experiments are conducted using representative Indonesian cities located within the Köppen climate classifications of Af (tropical rainforest) and Am (tropical monsoon) (Hakim, Edriawan, and Putra 2024; Meteoblue 2025). These locations exhibit considerable variation in solar radiation exposure, humidity profiles, and temperature distributions, thereby providing a robust and reliable framework for evaluating PCM performance under diverse tropical climatic conditions. For each combination of wall typology, PCM configuration, and climate zone, the optimization framework identifies a set of Pareto-optimal solutions that represent the most effective trade-offs among the three competing performance objectives (Abu-Hamdeh, Bantan, and Hatamleh 2022; Saxena, Rakshit, and Kaushik 2020; Zhang et al. 2022).

This study introduces five distinct dimensions of novelty.

a. Sector-Specific Orientation distinguishes this research from existing literature by focusing on the application of PCM-enhanced envelope systems within the hotel sector, which operates continuously throughout the year and is subject to persistently high thermal loads, unlike prior studies that primarily addressed residential or generalized commercial buildings (Wi, Chang, and Kim 2020).
b. Climate-Specific Focus emphasizes the tropical climatic context of Southeast Asia, particularly Indonesia, where a strong tourism industry coexists with climatic challenges that have been largely overlooked in PCM-related studies, including sustained high humidity levels, elevated ambient temperatures, and increased diurnal temperature variations.
c. Advanced Optimization Methods are employed through the application of multi-objective evolutionary algorithms capable of capturing nonlinear interactions among PCM properties, wall typologies, and climatic parameters, without relying on fixed melting temperatures or simplified envelope assumptions.
d. Lifecycle-Based Integration extends beyond short-term thermal performance assessment by incorporating life cycle cost (LCC) and CO_2 emissions as evaluation criteria, thereby enhancing the relevance of the framework for the hospitality sector, where long-term operational costs and environmental impacts are critical considerations for decision-makers (Zhang et al. 2022; Wei et al. 2022).
e. Multi-Criteria Decision Making (MCDM) techniques are applied to rank the design alternatives by prioritizing envelope configurations based on energy savings and payback periods, enabling stakeholders to identify optimal solutions according to specific investment priorities and performance objectives (Byrne et al. 2019; G. Wang et al. 2023).

Table 1. Comparative literature review: previous studies versus the current study

Reference	Climate context	Technique used	Key findings	Research gap addressed by current study
Saurbayeva et al. (2021)	General tropical (unspecified locations)	PCM in internal walls	18.2–42.7% energy savings	Lacks local climate specificity or wall type comparison
Aric et al. (2021)	Tropical monsoon	PCM applied to ceilings	~17% TEC and ~18% CO_2 reduction	Focuses on ceilings only; limited envelope scope
Kumar, Alam, and Sanjayan (2021)	Hot Australian climate	PCM + Aerogel + multi-objective analysis	Up to 65% TEC and 35% LCC savings	Non-Indonesian context; not hospitality-specific

Reference	Climate context	Technique used	Key findings	Research gap addressed by current study
Li et al. (2021)	Various climates in China	PCM in exterior walls with varied Tm	Max. 45.51% LCC reduction	No hotel sector focus; limited to residential use cases
Sovetova et al. (2020)	Tropical humid	PCM in wallboards	General performance gains (no CO_2/LCC quantified)	No lifecycle economic or emissions integration
Current Study	Af, Am, Aw, BSh zones in Indonesia	PCM integration in 4 wall types using NSGA-II	Up to 47.8% TEC, 52.96% CO_2, and 29.62% LCC savings	Focuses on hotels only; climate-material-tech synergy; decision support via MCDM; Indonesian-specific design model

This research hypothesizes that the incorporation of Phase Change Materials (PCMs) into hotel exterior wall systems, when appropriately calibrated to local climatic conditions, can achieve an optimal balance between energy efficiency and economic and environmental sustainability. The study is particularly significant in light of the increasing demand for intelligent design strategies that align with national objectives for zero-carbon construction, especially within the rapidly expanding tourism and hospitality sectors.

Methods

This study adopts a multi-objective optimization approach within the simulation process to support the integration of Phase Change Materials (PCMs) into building envelope systems, with the aim of facilitating the achievement of Net-Zero Energy (NZE) performance in hotel buildings located in tropical regions. Considering the high energy consumption and continuous operational nature of hotel facilities, particularly in tropical contexts such as Indonesia, the study develops a computational framework designed to systematically enhance energy efficiency, environmental performance, and economic viability. This framework integrates the Non-dominated Sorting Genetic Algorithm II (NSGA-II) with DesignBuilder as the modeling interface and EnergyPlus as the dynamic simulation engine, enabling the automated generation, simulation, and evaluation of multiple PCM-enhanced envelope design alternatives across different climate zones and wall typologies.

Within this framework, the evolutionary optimization algorithm (NSGA-II) is coupled with a robust dynamic building energy simulation platform (DesignBuilder powered by EnergyPlus). For each NSGA-II generation, DesignBuilder generates or modifies building models, which are subsequently simulated in EnergyPlus to calculate annual cooling energy demand, life cycle cost (LCC), and CO_2 emissions. These performance indicators are then fed back into the NSGA-II algorithm to update the solution population and establish Pareto-optimal fronts. This integrated modeling approach allows for a comprehensive parametric analysis of PCM configurations, including melting temperatures, layer thicknesses, and placement within various wall assemblies. Consequently, the study identifies optimal envelope design solutions capable of reducing cooling energy demand while simultaneously satisfying constraints related to life cycle costs and carbon emission mitigation.

To reflect typical hotel construction practices in Indonesia, four wall typologies were selected, namely brick masonry with interior plaster, concrete block construction, cast-in-place concrete walls, and earthen wall systems. These configurations were chosen not only because of their prevalence in local construction but also due to their differing thermal behaviors, enabling an evaluation of PCM performance across a range of thermal mass characteristics. The simulations were conducted using two commercially available PCMs: BioPCM, a biodegradable PCM with adjustable melting temperature ranges suitable for passive cooling applications, and InfiniteR PCM, a hydrocarbon-based material characterized by high thermal stability and frequent use in high-humidity environments. These materials were examined across multiple design variables, including melting temperature ranges from 22°C to 30°C, layer thicknesses between 1 cm and 5 cm, and integration positions within the wall assembly, namely inner, middle, and outer layers.

Table 2. Thermophysical properties of baseline envelope materials

Envelope	Layer	t (m)	K (W/m-K)	ρ (kg/m³)	Cp (J/kg-K)
The Roof	ferroconcrete	0.300	1.801	2501	841
	The roll of Asphalt	0.03	0.751	1101	1511
The Wall	The Brick	0.300	0.721	1921	841
The Floor	The Marble	0.009	3.501	2801	1001
	The Lime mortar	0.004	0.871	1801	1001
	The Gravel & sand	0.060	0.701	1801	1001
	The Reinforced concrete	0.400	1.801	2501	841
	Plaster	0.030	0.721	1861	841

Table 3. Thermal properties of selected PCMs (BioPCM 2023; 2024)

Compound	Tm (°C)	K (W/m-K) (liq/solid)	Cp (J/kg-K) (liq/solid)	ρ (kg/m³) (liq/solid)	LH (kJ/kg)	Type
The InfiniteRPCM	21,23, 35,28	0.54 / 1.09	3140 / 3140	1541 / 1541	200	Inorganic
BioPCM	21,23, 35,27, 28	1.50 / 1.80	2000 / 2000	2201 / 2301	225	Organic

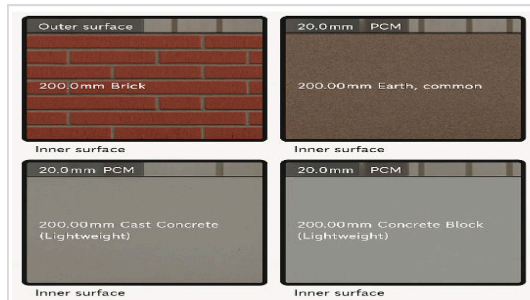

Figure 1. Wall envelope PCM integration configurations

Table 4. Climatic profiles of selected Indonesian cities

City	Climate	Lat (°)	Long (°)	Alt (m)	Temp Max (°C)	Temp Min (°C)	SR (kWh/m²/day)	WS (m/s)
Jakarta	Am	-6.21	106.86	8	34.5	25.0	4.93	2.21
Surabaya	Aw	-7.26	112.76	5	36.0	24.2	5.46	3.01
Medan	Af	3.59	98.66	27	33.1	23.6	4.69	1.81
Batam	Aw	-5.15	119.45	25	35.3	24.0	5.88	2.76
Pontianak	Af	0.04	109.35	3	34.2	25.2	5.65	2.41
Denpasar	Am	-8.66	115.23	9	33.0	24.8	5.03	1.96

Two primary optimization scenarios were established in this study. In the first scenario, the algorithm was designed to minimize Total Energy Consumption (TEC) and Life Cycle Cost (LCC), while the second scenario focused on minimizing TEC and annual CO_2 emissions. For each scenario, the NSGA-II algorithm generated a Pareto front, representing a set of optimal solutions in which improvement in one objective could not be achieved without a compromise in another. The application of a multi-criteria evaluation framework enabled transparent and systematic decision-making based on energy performance, economic feasibility, and environmental sustainability.

The envelope performance was assessed using three quantitative indicators corresponding to the case study parameters: annual envelope energy consumption (kWh), total life cycle cost (USD), which included installation, maintenance, and replacement costs over a 25-year period, and annual CO_2 emissions (kg/year) calculated using local electricity generation emission factors. In addition, the simulations verified compliance with thermal comfort requirements by maintaining operative indoor temperature limits between 23°C and 26°C, in accordance with hotel design standards.

Beyond the optimization process, a Multi-Criteria Decision Making (MCDM) model was employed to support stakeholders in identifying practically viable envelope solutions based on project-specific priorities. The considered preferences included return on investment, environmental impact, and payback period, which were evaluated through weighted ranking methods. This approach translated the optimization outputs into actionable design decisions that balanced technical performance with financial practicality.

The proposed research framework introduces several novel contributions to sustainable architectural design. First, it specifically targets the hospitality sector, which exhibits distinct operational characteristics and thermal behaviors compared to residential or office buildings. Second, it explicitly addresses tropical climatic conditions, which are often overlooked in mainstream PCM research despite their relevance to the rapidly expanding tourism industry in Southeast Asia. Third, it employs advanced optimization techniques capable of capturing nonlinear thermal behavior and complex interactions among PCM properties, wall materials, and climatic variables. Fourth, it adopts a life cycle–based perspective that enables evaluation of long-term performance beyond short-term thermal buffering effects. Finally, the framework integrates decision-making mechanisms that bridge scientific simulation with practical design implementation, allowing architects, engineers, and hotel developers to effectively apply the findings.

Overall, this approach establishes a robust analytical workflow for comparing and refining PCM-integrated passive envelope strategies in hotel buildings located in hot and humid climates. By addressing energy savings, cost efficiency, and carbon emission reduction, it provides a replicable and climate-responsive pathway toward achieving net-zero energy buildings in tropical regions.

Results and discussion

This section presents the results of a bi-objective optimization analysis applied to PCM-integrated wall systems for hotel buildings across six Indonesian cities, each representing a distinct tropical climate classification: Af (Pontianak and Medan), Am (Jakarta and Batam), and Aw (Denpasar and Surabaya). The optimization process combined NSGA-II with DesignBuilder–EnergyPlus, where NSGA-II generated candidate PCM wall configurations defined by melting temperature, thickness, and placement for each wall typology. DesignBuilder developed the corresponding building models, and EnergyPlus conducted annual simulations to compute Total Energy Consumption (TEC), Life Cycle Cost (LCC), and CO_2-equivalent emissions for each design alternative. Based on these simulations, Pareto fronts were generated for two scenarios: (1) TEC versus LCC and (2) TEC versus CO_2-equivalent emissions, from which the Pareto-optimal solutions illustrated in figures 4 and 3 were derived.

Figure 4 presents the relationship between TEC and CO_2 emissions for different wall typologies and climatic conditions. The optimization outcomes demonstrate that PCM integration effectively reduces both energy consumption and carbon emissions. Among the evaluated wall systems, earth-based walls exhibited the most pronounced performance improvements, followed by brick masonry, cast-in-place concrete, and concrete block walls. Specifically, annual energy consumption ranged from 28.24–32.42 kWh/m² for brick walls, 26.92–31.40 kWh/m² for concrete blocks, 27.59–32.96 kWh/m² for cast-in-place concrete, and 29.00–35.79 kWh/m² for earth-based walls. Corresponding CO_2 emissions varied between 16.42–21.02 $kgCO_2$-eq/m² for brick walls, 16.23–18.24 $kgCO_2$-eq/m² for concrete blocks, 16.40–21.71 $kgCO_2$-eq/m² for cast concrete, and 16.51–22.45 $kgCO_2$-eq/m² for earth-based wall systems.

Figure 3 illustrates the optimization results for Total Energy Consumption (TEC) versus Life Cycle Cost (LCC). The LCC values varied depending on construction typology, material costs, and the resulting thermal performance of the envelope systems. Brick wall configurations exhibited LCC values ranging from 67.18 to 119.90 USD/m², while concrete block walls ranged between 63.17 and 110.22 USD/m². Cast-in-place concrete walls recorded LCC values from 73.25 to 121.84 USD/m², whereas earth-based wall systems showed higher variability, ranging from 75.27 to 134.09 USD/m². These variations are primarily attributed to regional electricity tariff differences as well as disparities in thermal efficiency resulting from PCM integration.

To evaluate relative performance improvements, the optimized PCM-integrated wall systems were compared with baseline (non-PCM) configurations. As presented in Figure 2, the results demonstrate the extent of energy savings achieved across the investigated cities. Maximum energy efficiency savings (MEES) were recorded at 47.80% for earth walls, followed by 44.74% for brick walls, 42.15% for cast-in-place concrete, and 39.85% for concrete block walls. These findings indicate that wall systems with higher thermal mass, particularly earth and brick, when enhanced with PCM, significantly improve indoor thermal regulation and reduce cooling energy demand.

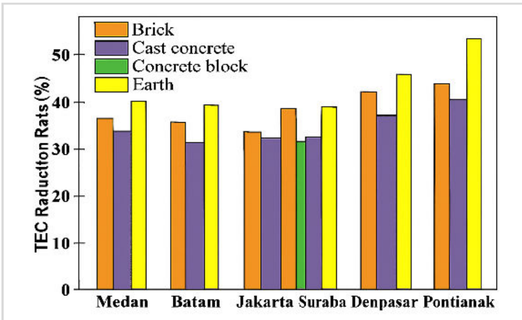

Figure 2. Reduction in energy consumption across the evaluated urban areas

With respect to carbon emissions, figure 4 shows CO_2 reductions of 52.96% for earth walls, 47.18% for brick walls, 39.32% for cast-in-place concrete, and 35.88% for concrete block systems. These reductions are a direct consequence of decreased energy consumption resulting from the integration of PCM-enhanced envelope designs.

Figure 3 further highlights the economic benefits achieved across the analyzed regions. Maximum cost efficiency savings (MCES) were observed for earth wall systems at 29.62%, followed by cast-in-place concrete at 26.34%, brick walls at 21.99%, and concrete block walls at 17.83%. The highest economic benefits were recorded in Denpasar, classified under the Bsh climate zone, where electricity tariffs are relatively high, whereas the lowest savings were observed in Pontianak (Af climate), where lower electricity costs reduced the relative economic advantage of PCM implementation.

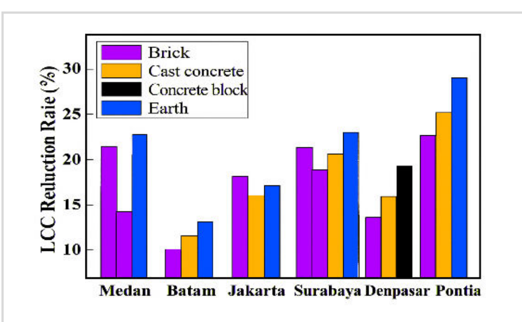

Figure 3. Economic savings achieved in the analyzed regions

Across both the TEC–LCC and TEC–CO_2 optimization scenarios, the NSGA-II algorithm generated distinct Pareto fronts that reflect the inherent trade-offs among energy efficiency improvements, emission reductions, and increased envelope investment costs. Solutions located near the inflection point of the Pareto curve represent optimal design compromises, where relatively small increases in LCC result in disproportionately large reductions in TEC and CO_2 emissions. These solutions provide valuable guidance for hotel owners, architects, and designers when making informed decisions under varying climatic and economic conditions.

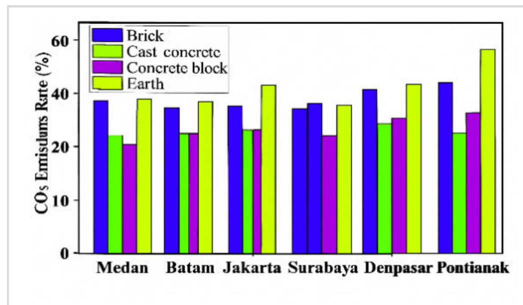

Figure 4. Reduction of CO_2 emissions in the selected urban environments

The obtained results are consistent with findings reported in previous studies. For instance, Abbasian-Naghneh and Kalbasi reported annual cost reductions of 19.8%, alongside energy and CO_2 savings of 23.6%. Saurbayeva et al. documented energy reductions ranging from 18.2% to 42.7% in tropical climates, while Aric et al. observed savings of 16.8–17.2% in TEC and approximately 18.4% in CO_2 emissions. Kumar et al. reported TEC and CO_2 reductions of up to 65%, along with LCC savings of 35% in Australian contexts. Similarly, Li et al. identified an average LCC reduction of 22.35%, with maximum savings reaching 45.51%. Comparable long-term performance improvements were also reported by Sovetova et al. and Yang et al.

The preferred PCM configurations by climate zone, wall type, and city, defined by melting temperature (Tm), thickness (t), and placement (P), are summarized in table 5. Across all locations, positioning the PCM layer on the exterior side of the wall (P1) consistently delivered optimal thermal and energy performance, corroborating findings from previous studies. This configuration enhances daytime heat absorption and promotes delayed heat release during nighttime hours, thereby reducing cooling loads.

From a material performance perspective, PCM 1, characterized by a higher latent heat capacity, demonstrated superior energy and cost efficiency compared to PCM 2, which required substantially greater thicknesses to achieve comparable performance. The selection of an appropriate melting temperature was also critical: optimal Tm values ranged between 23–27°C for Af climate zones and 25–29°C for Am, Aw, and Bsh zones. These findings align closely with those of Saffari et al., who identified optimal PCM melting temperature ranges of 24–29°C for tropical environments.

Although increased PCM thickness led to greater energy savings, it also resulted in higher material costs, thereby reducing LCC efficiency. Thicker PCM layers (up to 0.03 m) were associated with maximum energy efficiency savings, whereas thinner layers (0.01–0.02 m) proved more economically viable, particularly in climates such as Bsh, where balancing energy savings and cost efficiency is critically important.

Discussion

The optimization outcomes discussed above demonstrate that the integration of phase change materials (PCMs) as an enhancement strategy for building envelopes offers substantial potential for improving the energy, environmental, and economic performance of hotel buildings located in tropical climates. By systematically exploring an extensive design space of PCM-integrated wall configurations across six Indonesian cities, this study employed a robust framework combining NSGA-II with DesignBuilder–EnergyPlus, rather than relying on conventional trial-and-error approaches. Through this process, optimal combinations of PCM melting temperature, layer thickness, and placement were identified that simultaneously improved Total Energy Consumption (TEC), Life Cycle Cost (LCC), and CO_2 emissions. Within the broader context of sustainable building design in hot-humid and hot-dry climates, these findings contribute to a deeper understanding of how wall systems can be effectively adapted to address the diverse climatic conditions found across Indonesia.

One of the most significant findings is the substantial reduction in total energy consumption observed across all climatic zones and wall typologies. In particular, the results highlight the pronounced synergistic effect achieved when PCMs are combined with high thermal mass materials, such as earth and brick. This synergy can be attributed to the interaction between latent heat storage provided by the PCM and the inherent thermal inertia of massive wall materials. Similar synergistic behavior has been reported in earlier studies, which documented energy savings in the range of 18–32 percent, closely aligning with the 39–48 percent range observed in the present study. This consistency reinforces the effectiveness of PCM-based envelope strategies under a wide spectrum of tropical climate conditions.

As summarized in Table 5, the results further indicate that earth-based wall systems equipped with externally positioned BioPCM outperform other wall typologies across all three evaluation criteria, namely TEC, LCC, and CO_2 emissions. In addition, it is noteworthy that the internal placement of PCM layers (P3) within brick wall assemblies achieved performance levels comparable to external PCM configurations, particularly in terms of cooling load reduction in monsoon-dominated (Am) climate zones such as Jakarta and Surabaya. This observed variation highlights the necessity of climate-specific optimization strategies when implementing PCM technologies, reinforcing the notion that optimal PCM solutions must be carefully aligned with local climatic conditions and building characteristics.

Table 5. Summary of energy, economic, and environmental performance of PCM-Wall configurations in Indonesian tropical hotels

Wall type	PCM type	PCM placement	Melting temp (°C)	Thickness (m)	Total energy reduction (%)	LCC savings (%)	CO_2 emission reduction (%)
Earth Wall	BioPCM	P1 (Exterior)	25	0.02	**47.8**	29.62	**52.96**
Brick Wall	InfiniteR PCM	P3 (Interior)	27	0.01	41.35	26.70	48.80
Concrete Cast	BioPCM	P1 (Exterior)	26	0.01	39.32	24.50	43.67
Concrete Block	InfiniteR PCM	P1 (Exterior)	27	0.02	35.88	22.31	40.45

Wall type	PCM type	PCM placement	Melting temp (°C)	Thickness (m)	Total energy reduction (%)	LCC savings (%)	CO_2 emission reduction (%)
Brick Wall (Am)	InfiniteR PCM	**P3 (Interior)**	**27**	**0.02**	**45.10**	**27.50**	**49.90**

Earth walls with exterior BioPCM demonstrated the most substantial performance across all three evaluation criteria, as summarized in table 5. However, in monsoon-type Am climates, such as those in Jakarta and Surabaya, interior placement (P3) within brick walls yielded nearly equivalent performance, particularly regarding latent cooling reduction. This observation underscores the importance of climate-specific strategies when planning PCM integration.

Consistent with prior studies, exterior PCM placement (P1) emerged as the most reliable configuration across all wall types and climate zones. This result confirms the thermal advantage of positioning PCM at the building's outer shell, effectively reducing heat ingress, minimizing interior cooling loads, and enhancing passive thermal regulation. Such performance is particularly critical in hotels, where occupant comfort is a primary design consideration.

The focus on the hospitality sector further emphasizes the practical relevance of these findings. Hotels operate at high occupancy levels year-round, making energy efficiency a crucial factor in sustainable business operations. Beyond cost reduction, PCM-enhanced envelopes substantially improve thermal comfort, a key determinant of guest satisfaction in the hospitality industry. Moreover, PCM deployment offers modular flexibility, facilitating both retrofitting and new construction initiatives in alignment with national green building objectives and global net-zero tourism goals (Byrne et al. 2019; Gilbert, Latief, and Detty 2024).

Nonetheless, trade-offs remain inherent in PCM application. While thicker PCM layers maximize operational energy savings (MEES), they also incur higher material costs and diminishing returns on life cycle cost (LCC), highlighting the tension between environmental performance and economic feasibility. Multi-objective optimization tools, such as the NSGA-II algorithm coupled with DesignBuilder–EnergyPlus employed in this study, are therefore essential for balancing these competing priorities, consistent with observations in related PCM optimization research (Kim and Clayton 2020; Markarian and Fazelpour 2019).

Conclusions

This study applied a multi-objective genetic algorithm (NSGA-II) integrated within a DesignBuilder–EnergyPlus simulation framework to optimize the thermal envelopes of hotel buildings in six Indonesian cities, representing diverse Köppen climate zones (Af, Am, Aw, Bsh). The optimization targeted three critical performance metrics: total energy consumption (TEC), life cycle cost (LCC), and CO_2-equivalent emissions. Key PCM design parameters including melting temperature, layer thickness, and placement were systematically varied, and two PCM types were evaluated under dual-objective scenarios (TEC-LCC and TEC-CO_2 minimization).

The results demonstrate that PCM-integrated envelopes significantly improve hotel energy performance in tropical climates. TEC reductions ranged from 31.21% to 47.80%, with earth and brick walls achieving the highest savings due to the synergistic effects of high thermal mass and latent heat storage. Climate-specific variation was evident, with Bsh regions experiencing the greatest benefits.

Economically, PCM application yielded LCC reductions between 3.47% and 29.62%, with the largest returns observed in areas with high electricity tariffs and cooling demand, such as Denpasar. These outcomes affirm the cost-effectiveness of PCM deployment in energy-intensive hospitality operations.

Environmentally, a strong correlation was observed between energy savings and CO_2 mitigation. CO_2 emissions decreased by up to 52.96% in earth wall systems, highlighting the significant environmental advantages of optimally implemented PCM solutions.

Optimal design parameters were identified as melting temperatures between 23–29 °C, layer thicknesses from 0.01–0.03 m depending on climate, and consistent superiority of exterior PCM placement.

The proposed optimization framework offers a flexible, data-driven methodology for designing energy-efficient, climate-responsive hotel envelopes in tropical regions. It supports Indonesia's eco-tourism development objectives and contributes to global net-zero ambitions. Future research should incorporate dynamic occupancy patterns, humidity control, and integration with intelligent building control systems to enhance real-time performance and occupant comfort in hospitality environments.

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