



Assessment of Energy Flexibility of Residential Buildings with Phase Change Materials in Uzbekistan Using the Flexibility Evaluation Tool

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Abstract. Uzbekistan's drastically changing continental climate and rapidly rising residential energy consumption mean that structures that have demand-side flexibility to facilitate the incorporation of renewable energy are needed shortly. The present research assesses the energy flexibility of residential buildings augmented with phase change materials (PCMs) utilising the standardised framework of the IEA EBC Annex 67 Flexibility Evaluation Tool (FET). We used dynamic Modelica simulations to get hourly heating and cooling loads for both reference and demand-responsive operation. An orthogonal experimental design (OED) comprising six PCM parameters and five levels was utilised to ascertain the predominant material properties affecting flexibility indicators, such as flexibility efficiency (Eflex), shifted loads (Sflex), peak shaving (PS), ramp-rate reduction (RR), and cost-weighted savings. The results indicate that PCM density, thickness, and latent heat significantly facilitate long-duration load shifting, but melting temperature predominantly influences peak demand decreases. The results show that better PCM integration greatly increases the flexibility of residential energy use in Uzbekistan, which helps with grid stability and the use of renewable energy.

Keywords: Energy Flexibility, Phase Change Materials, Residential Buildings, Heating Loads, Flexible Operation, Shifted Loads.

1 Introduction

Energy flexibility is now an important feature for buildings in power systems with a lot of variable renewables. It lets heating and cooling loads be moved around in response to changes in electricity prices, CO₂ levels, or grid limits without making the inside less comfortable [1-3]. IEA EBC Annex 67 gives standardised indicators and methodological principles for measuring this kind of flexibility. For example, it includes the use of predefined demand response (DR) signals and the quantification of structural thermal storage [2,4]. The Flexibility Evaluation Tool (FET) was created as

a useful framework that combines dynamic simulations with cost- or emission-weighted metrics to make flexibility indices like load shifting potential, self-consumption, and the Building Energy Flexibility Index (BEFI) [3,5]. FET has been utilised in various international studies; however, the majority concentrate on European climates and standard building configurations, with minimal emphasis on phase change materials (PCMs) or continental areas like Central Asia.

Many people know that PCMs can improve the energy performance of buildings by storing latent heat, which increases thermal inertia [6-8]. Many studies show that PCM-integrated walls and passive solar systems can greatly lower heating and cooling loads while keeping indoor temperatures stable [6-8]. In Uzbekistan's sharply continental climate, PCM-integrated Trombe walls have shown that they can save more than 50% of heating energy. In cities like Namangan, where PCM properties have been optimised, performance has been shown to improve even more [7,8]. Nevertheless, current regional studies predominantly emphasise energy efficiency and comfort, neglecting the flexibility potential of PCM-enhanced buildings - especially in standardised demand response scenarios utilising tools like FET.

The Taguchi method provides an effective orthogonal experimental design (OED) to assess the impact of various PCM parameters while reducing simulation effort, thereby addressing multi-factor sensitivity in PCM performance [9-11]. However, there has been no research that integrates Taguchi-based PCM optimisation with FET-based flexibility evaluation for residential buildings in Uzbekistan. This research addresses this deficiency by quantifying the energy flexibility of PCM-enhanced residential buildings through FET and by pinpointing essential PCM parameters that influence flexibility under typical DR conditions.

2 Method and materials

2.1 Flexibility Evaluation Framework

The flexibility assessment follows the principles defined in IEA EBC Annex 67, which requires three synchronized input time series to characterize building response under flexible operation: $L_{ref,t}$ - the reference thermal or electrical load at time step t , representing the building operation without any demand response (DR) intervention. Units may be expressed in kW or kW/m² to enable area-normalized comparisons. reference load without flexibility; $L_{flex,t}$ - the flexible load at time step t , representing the building's consumption profile under DR actions or demand-responsive HVAC control.load under flexible operation [kW or kW/m²]. C_t - cost/penalty signal (e.g., €/kWh, gCO₂/kWh, or primary energy/kWh).

2.2 Data and Simulation Setup

Hourly thermal loads were generated using dynamic building simulations in Modelica. Meteorological inputs for Tashkent were obtained from regional climate datasets.

Two simulation models were established: reference operation that includes a baseline HVAC control strategy representative of case 600 from ASHRAE 140 Standard with PCM-enhanced and conventional envelopes; flexible operation, where simulations including temporary set-point modifications, load shifting strategies, and forced DR events.

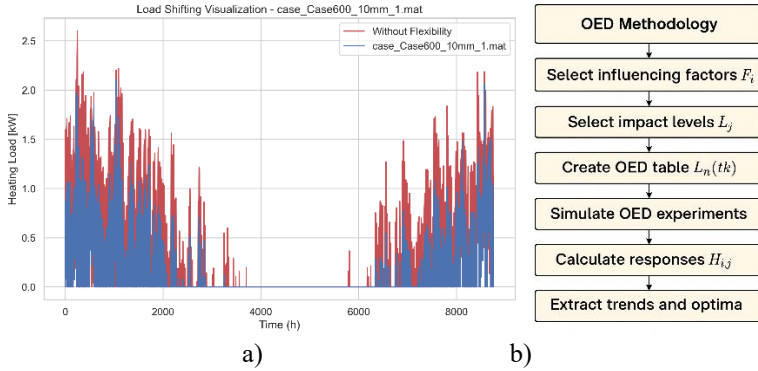


Fig 1. Load shifting visualization (a) and (b) flowchart for the OED methodology.

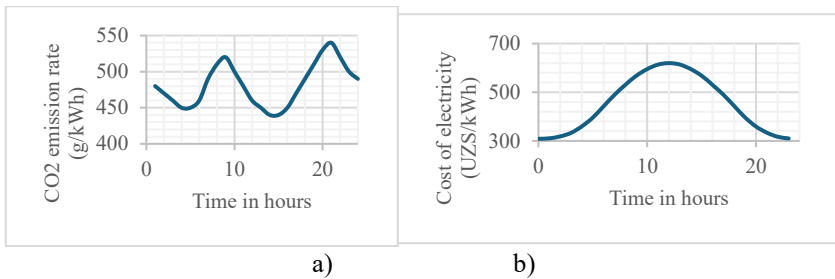


Fig 2. Penalty functions. (a) time-dependent CO2 emission rate and (b) variation of cost of energy over daytime.

The cost function C_t was parametrized for three distinct DR scenarios: -Time-varying electricity tariffs (Fig 2b); -Marginal CO₂ emission factors (Fig 2a); -Residual load (Fig 1). All simulations were performed with an hourly time step ($\Delta t=1$ hour), although the framework supports arbitrary temporal resolution.

2.3 Orthogonal experimental design (OED)

The OED method selects representative points from the full factorial experimental design (FED) in a way that these points are uniformly distributed within the test range and thus can represent the overall situation. This method is highly efficient for arranging multifactor experiments with optimal combination levels. If an orthogonal array of n trials has k factors of t levels, it is denoted as $L_n(t^k)$. OED has several advantages: (1) the data points are evenly distributed; the number of trials needed to complete the experiment is relatively small; (3) the test results can be analyzed through range and var-

iance analysis. OED has the following characteristics: (1) fractional FED is implemented instead of full FED, and (2) the full experiment is examined through analysis of the fractional experiment. This work estimates the thermal performance of buildings by analyzing six influencing factors of PCM layers integrated in vertical building walls (thickness, melting temperature, latent heat of fusion, density, specific heat capacity, and thermal conductivity) at five impact levels (Fig 1b).

2.4 Selection of the influencing factors of the PCMs

PCM parameter is varied independently. The main idea is to determine the highest and lowest impacts among a variety of individual factors. Factors A, B, C, D, E, and F correspond to the thickness (mm), melting temperature ($^{\circ}\text{C}$), latent heat of fusion (J/g), density (g/cm^3), specific heat capacity (J/g·K), and thermal conductivity (W/m·K), respectively. The temperature range of phase transition was kept at 3 K.

2.5 Mathematical Formulation

All indicators and intermediate variables are defined in discrete time steps $t = 1, 2, \dots, T$ with time interval Δt .

2.6 Deviation and Energy Balances

The instantaneous load deviation is defined as:

$$D_t = L_{flex,t} - L_{ref,t} \quad (1)$$

A positive deviation indicates increased consumption under flexible operation (e.g., rebound heating), whereas a negative deviation represents reduced consumption during a DR event. The total energy consumption for the reference and flexible scenarios is computed as:

$$E_{ref} = \sum_{t=1}^T L_{ref,t} \Delta t \quad (2)$$

$$E_{flex} = \sum_{t=1}^T L_{flex,t} \Delta t \quad (3)$$

Both quantities represent annual (or seasonal) thermal demand in kWh.

2.7 Cost-Weighted Cumulative Loads

To directly link building flexibility to economic or environmental signals, each load value is weighted by the external signal:

$$W_{ref} = \sum_{t=1}^T C_t L_{ref,t} \Delta t \quad (4)$$

$$W_{flex} = \sum_{t=1}^T C_t L_{flex,t} \Delta t \quad (5)$$

These indicators quantify the cost, CO₂ impact, or primary energy use of each operating mode.

2.8 Savings and Efficiency of Flexible Operation

The absolute savings obtained from flexible operation are:

$$S = W_{ref} - W_{flex} \quad (6)$$

The flexibility efficiency expresses the relative improvement:

$$E_{flex} = 100\% \times \frac{W_{ref} - W_{flex}}{W_{ref}} \quad (7)$$

A higher E_{flex} denotes more effective shifting to low-cost or low-emission periods.

2.9 Shifted Flexible Loads Indicator

This indicator quantifies the magnitude of total load movement (regardless of direction):

$$S_{flex} = 100\% \times \frac{\sum_{t=1}^T |L_{flex,t} - L_{ref,t}| \Delta t}{\sum_{t=1}^T L_{ref,t} \Delta t} \quad (8)$$

A value of 0% indicates no load shifting, while higher values denote more active flexibility.

2.10 Event-Level Step Response Parameters

In the step-response characterization: τ : delay between signal change and system response [s]; Δ : maximum change in demand [W]; α : time to reach lowest demand [s]; β : duration of reduced demand [s]; A : total decreased energy [J]; B : total increased (rebound) energy [J]; These are computed as:

$$A = \sum_{t \in event} \max(0, L_{ref,t} - L_{flex,t}) \Delta t \quad (9)$$

$$B = \sum_{t \in event} \max(0, L_{flex,t} - L_{ref,t}) \Delta t \quad (10)$$

Derived metrics:

$$r = \frac{B}{A} \quad (\text{rebound ratio}) \quad (11)$$

Finally, the payback time quantifies how long it takes until the cumulative deviation returns to zero:

$$T_{payback} = \min\{t: \sum_{k=t_0}^t D_k \Delta t = 0\} - t_0. \quad (12)$$

2.11 Peak and Ramp Metrics

Peak shaving evaluates the ability to reduce maximum demand:

$$PS\% = 100\% \times \frac{\max_t L_{ref,t} - \max_t L_{flex,t}}{\max_t L_{ref,t}} \quad (13)$$

Ramp rate flexibility measures the building's capacity to moderate rapid fluctuations:

$$RR\% = 100\% \times \frac{\max_t |L_{ref,t} - L_{ref,t-1}| - \max_t |L_{flex,t} - L_{flex,t-1}|}{\max_t |L_{ref,t} - L_{ref,t-1}|} \quad (14)$$

Higher values of PS and RR indicate superior grid-support capabilities.

3 Results and discussion

3.1 Static Load-Related and Dynamic Response Metrics

Static load-related metrics (A , B , Δ) and dynamic response metrics (α , β) were influenced by the six PCM factors and they show distinct influence patterns. Density ($X4$) consistently emerges as one of the strongest contributors, especially for A (Fig 3a), B , and Δ , while melting temperature ($X2$) strongly governs parameter B and also significantly affects Δ . Thickness ($X1$) has a moderate role, mainly influencing A and B .

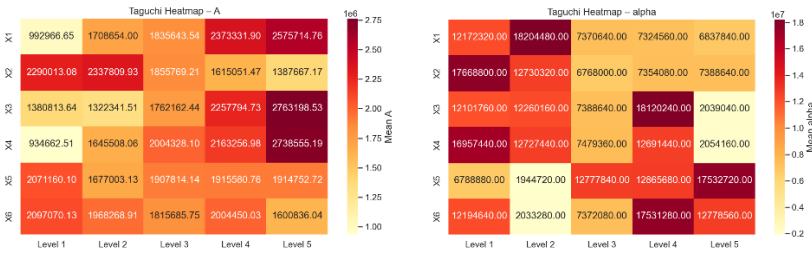


Fig 3. An example illustration of Taguchi heatmaps of parameters influences: (a) represents static load-related metrics (A) and (b) dynamic response metrics (α).

In contrast, the dynamic response parameters α (Fig 3b) and β are dominated by latent heat ($X3$), specific heat ($X5$), and thermal conductivity ($X6$), indicating that transient heat storage and transport properties control dynamic behavior. It follows to note that, static load-related metrics depend primarily on density, melting temperature, and latent heat, whereas dynamic parameters are controlled by thermophysical properties governing heat absorption, release, and conduction.

3.2 Energy-Based Flexibility Metrics (Eflex, Savings, Sflex)

The energy-related flexibility indicators - Eflex, Savings, and Sflex - show highly consistent influence patterns across the OED results. In all three metrics, density ($X4$) is the dominant factor, contributing approximately 32-36%, confirming that the mass and volumetric heat capacity of the PCM layer strongly affect the building's ability to shift and store thermal energy over longer periods.

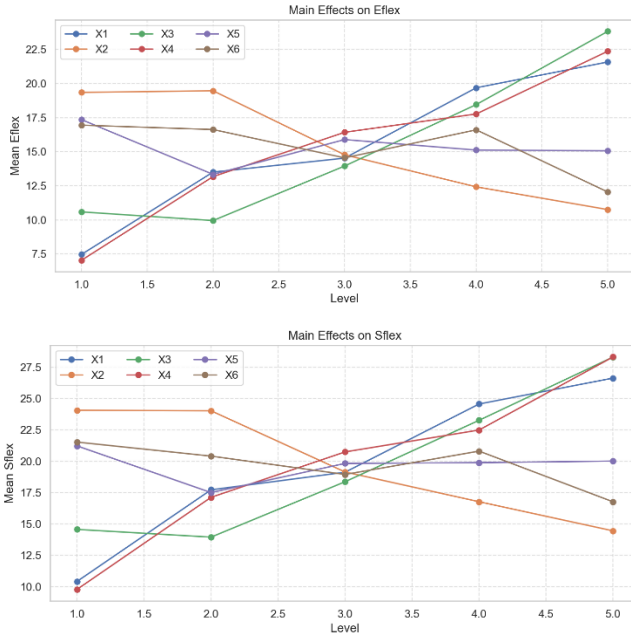


Fig 4. Energy-Based Flexibility Metrics (Eflex, Sflex)

Thickness (X1) and latent heat of fusion (X3) also exhibit substantial influence (22-28%), indicating that greater PCM volume and higher storage capacity increase the building’s capability to reduce cost-weighted energy consumption (Eflex), enhance absolute energy savings, and shift larger portions of the heating/cooling load (Sflex). In contrast, melting temperature (X2) plays only a secondary role in these energy-based indicators, while specific heat (X5) and thermal conductivity (X6) show minimal impact (<5%), meaning they contribute little to long-duration thermal load shifting compared with mass and latent-storage-related mechanisms.

3.3 Power and Dynamic-Response Metrics (PS and RR)

The power-oriented metrics - peak shaving (PS) and rebound ratio (RR) - exhibit distinct influence patterns that reflect short-term thermal dynamics rather than cumulative energy performance.

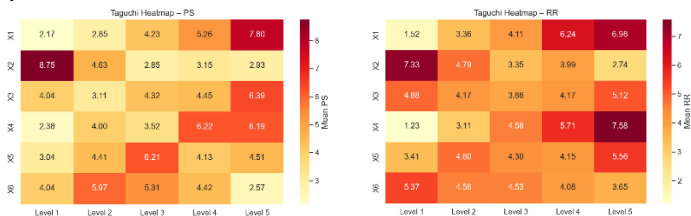


Fig 5. Taguchi heatmaps for PS and RR.

For PS, the most influential parameter is melting temperature (X2, 30.6%, Fig 5), showing that aligning the PCM phase change point with peak outdoor or indoor temperature ranges is essential for reducing maximum heating or cooling power. Thickness (X1) and density (X4) follow, each contributing 13-28%, indicating that both stored energy volume and material mass affect peak load moderation. For RR, however, density (X4) overwhelmingly dominates (40%), confirming that heavier PCM layers with greater thermal inertia create larger rebound effects after a demand-response event. All remaining factors—especially thermal conductivity (X6) and specific heat (X5)—contribute only marginally. One should note that PS is governed mainly by the temperature of phase transition of PCMs, while RR depends principally on the thermal inertia introduced by PCM mass, demonstrating a clear separation between short-term power effects and long-term energy flexibility behavior.

4 Conclusion

The current study utilised the IEA EBC Annex 67 Flexibility Evaluation Tool (FET) to evaluate the energy flexibility of residential structures in Uzbekistan and to quantify the impact of phase change materials (PCMs) on flexible demand operation. We used thorough Modelica-based simulations and an orthogonal experimental design to see how the features of PCM affect important flexibility indicators as Eflex, Sflex, PS, RR, and Savings. The findings indicate that PCM integration markedly improves the building's capacity to manage heating loads, lower energy expenses and emissions during peak penalty periods, and facilitate low-carbon grid functionality. Density, thickness, and latent heat were the most important elements for long-term energy shifting. Melting temperature was the most important factor for short-term peak shaving. The results show that PCM-enhanced envelopes can help Uzbekistan's acute continental climate by giving people more options on the demand side and supporting the growing use of renewable energy sources. In general, the study shows how important it is to optimise materials in order to make buildings that respond to the grid. It also gives a methodological basis for future building design in Central Asia that focusses on flexibility.

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