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Envelope–climate Interactions and Cooling Energy Intensity in Hot-arid Hospitality Building: A Multi-model Empirical Analysis for Rajasthan

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Abstract

The envelope building is one of the significant indicators of the cooling energy intensity of the hotels located in the hot-arid areas with the long cooling seasons and the high level of solar insolation, which makes the energy demand. This paper analyses the relationship among the envelope parameters, climatic conditions, and operating features of hotel constructions in the four cities of Rajasthan such as Jaipur, Jodhpur, Jaisalmer, and Bikaner. The data on the 3-star, 4-star, and 5-star hotels was gathered into a dataset based on publicly available energy benchmarks and climatic data. Four linear regression models with interaction terms were estimated to determine the sensitivity of cooling energy intensity to the glazing U-value, SHGC, window-to-wall ratio (WWR), shading depth, solar reflectance index (SRI), and cooling degree days (CDD). The findings indicate that climatic conditions (CDD) produce the greatest positive rate on cooling loads, and shading and high-SRI roofs are the ones with the greatest energy savings. Interaction effects between WWR and SHGC confirm the benefits of holistic envelope strategies. Fixed effects at the city level provide evidence that Jaisalmer and Bikaner have the highest cooling intensities, and thus are a retrofit priority. The results offer practical recommendations for envelope retrofit interventions and can inform policy interventions in India's hotel industry. The methodological approach—parametric regression, sensitivity mapping, and city-level comparisons—provides a replicable strategy for climate-responsive building energy planning for other hot–arid cities.

Keywords: Building Envelope, Energy Intensity, Hot–arid Climate, Hotel Buildings, Regression Analysis, Retrofit Strategy.

Introduction

The space cooling energy has become one of the most demanding energy requirements in building sector in hot-arid areas. Summers are quite long, solar radiation is very high and ambient temperatures remain quite high which makes buildings of such buildings a great burden in terms of thermal load that generates a lot of demand on mechanical cooling systems (1, 2). The hospitality industry in India, especially in tourist driven cities like Jaipur, Jodhpur, Jaisalmer and Bikaner, has a high cooling requirement because the offices are occupied through out, they are open all night and thermal comfort is of utmost importance. These attributes make hotels to be one of the most energy consuming forms of commercial buildings. Cooling is also the quickest expanding end use in buildings globally, and it is an important contributor to peak power consumption and escalating carbon emissions (3). To deal with this challenge, it is necessary to gain a better insight into the interactions between building envelope properties and climatic conditions and architectural typologies to affect cooling energy performance (4). Nevertheless, the majority of design criteria and retrofit recommendations are based on generalized energy regulations that tend to ignore intra-climatic differences and building-specific peculiarities (5). The architectural styles in use in the traditional architectural structures of the heritage hotels in Rajasthan, namely, its use of courtyards, thick masonry, and deep overhangs, shows the climate-receptive design approaches that lower cooling loads using passive design strategies (6, 7). Such architectural characteristics are very informative to the modern-day building design, as it implies that a blend of old techniques

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with new technologies would help to decrease the dependence on the mechanical cooling systems to the minimum. In spite of this possibility, there are very few empirical studies that have systematically studied the parameters of envelopes, climate variables and building typologies in the hospitality industry of hot-arid Indian cities (8). The construction industry contributes significantly to the overall energy consumption and greenhouse gas emission in the world and in particular in places where cooling accounts to the majority of building energy requirements. The last decades have seen a change in research direction as opposed to the traditional principles of passive design towards the more sophisticated energy modelling and simulation methods to enhance building performance and sustainability.

Still, a number of researches demonstrate the role of the envelope optimization to minimize cooling loads. As an example, a study based on parametric simulations under hot-arid climatic conditions explored insulation thicknesses, U-values of windows, infiltration levels and building orientation in order to conform to ASHRAE Standard 90.1 (9). Through these analyses it was established that high-technology glazing like thermochromic glazing and phase change materials (PCM), and photovoltaic integration has the potential to save up to 34 percent of energy used.

The studies of high-rise residential buildings in the humid regions also testify to the vitality of the envelope design and internal load parameters (10). There are also strategies of hybrid passive active cooling. In one study, evaporative cooling system with secondary envelopes was shown to potentially cut down the cooling energy consumption by up to 57 percent when it was hot and humid in summer (11). Although such systems hold a lot of potential, their reliance on water sources can make them scalable in arid areas. On the same note, thermal comfort and indoor temperature in desert climates have been reported to be enhanced by integrated passive systems which comprised of solar chimneys, wind towers and the use of phase change materials (12).

City level issues can also affect the performance of buildings. A study conducted in Qatar has been able to determine that the effects of urban heat islands (UHI) can lead to a 10 percent addition to cooling energy consumption during peak cooling seasons (13). These findings demonstrate the need to take into account microclimatic conditions and urban morphology as a building design process. Modelling studies at the district level also show the use of archetype buildings in estimating the cooling load and in planning infrastructure investment of the district cooling system (14).

Photovoltaic-based renewable energy sources are able to cut down on CO2 emissions due to the cooling process by a huge margin and at the same time can be economically feasible (15). Even straightforward passive methods like the construction of orientation and shading may reduce cooling energy consumption by up to 19% (16). Nevertheless, climate forecasts show that cooling demand would be boosted by 13-67 percent by the century-end with regard to building traits (17). Further passive mitigation measures such as evaporatively cooled windows, and district and urban-scale mitigation can also continue to lower cooling energy in stocks of buildings (18-20).

In general, these are some of the main insights constantly highlighted in the literature. Envelopes optimization is still at the core of minimizing cooling; there should be climate-specific performance (9). The heat islands and the district energy systems in the urban scale also influence greatly the performance of buildings (21, 22). Moreover, the large-scale use of innovative cooling technologies is not usually feasible in economic terms, due to policy obstacles. Although there is a massive technological breakthrough (23), there are still gaps in the empirical evidence, urban scale data, and policy integration frameworks (24, 25).

The research objectives are as follows:

To develop a city-resolved empirical dataset and quantify the influence of key envelope parameters (U-value, SHGC, WWR, shading depth, SRI) and climatic drivers (cooling degree days) on cooling energy intensity using multi-model regression analysis.

To identify contextual effects by incorporating architectural typology interactions and city-level fixed effects that capture micro-climatic heterogeneity and nonlinear relationships between envelope design and climate.

To translate modelling outcomes into practical insights by deriving parameter sensitivities and prioritizing envelope retrofit strategies suitable for Rajasthan's hot–arid hospitality sector.

Methodology

Study Area and Context

The study site of the research is an arid and hot climate area of Rajasthan, India which has a significant influence on the building energy performance due to its large cooling seasons, extreme daytime temperatures, and large sun insolation hours. The four big urban agglomerations, Jaipur, Jodhpur, Jaisalmer, and Bikaner were selected to be examined in depth. The study was conducted in the hot-arid region of Rajasthan, India, where long cooling seasons, extreme daytime temperatures and high solar exposure significantly influence building energy performance. Four major urban centres—Jaipur, Jodhpur, Jaisalmer and Bikaner—were selected to represent variations in microclimatic conditions, urban morphology and tourism-driven hospitality activity. The approximate city-centre geographical coordinates of the study areas are Jaipur (26.9124° N, 75.7873° E), Jodhpur (26.2639° N, 73.0090° E), Jaisalmer (26.9157° N, 70.9083° E) and Bikaner (28.0271° N, 73.3022° E). These coordinates represent the approximate geographical locations of the study areas rather than the precise locations of individual hotels.

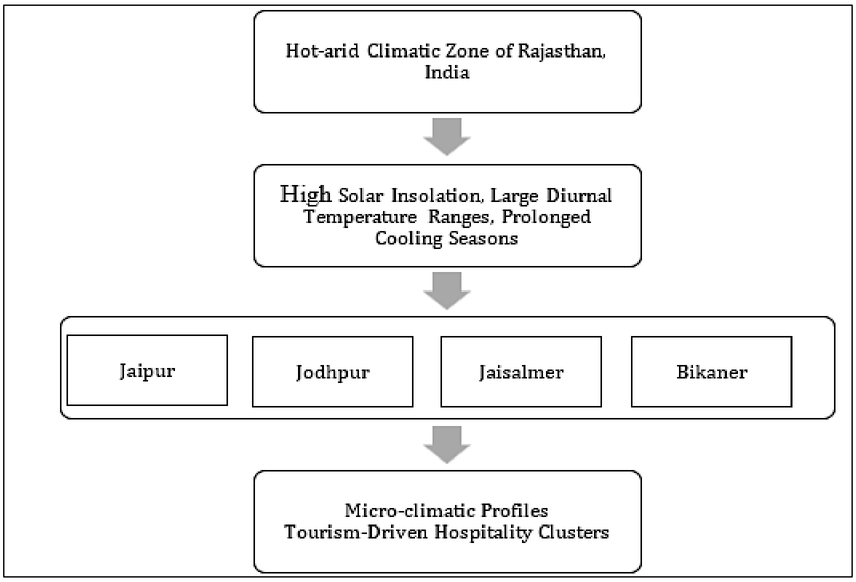

Figure 1: Conceptual Framework for Defining the Study Area

The formal structure as indicated in Figure 1 was used to delimit the study area to be analyzed in order to examine the building envelope energy performance under hot-arid climate condition in Rajasthan. The study area, which is hot and arid zones of Rajasthan, is conceptually related to five fundamental aspects, namely definition of climatic zone, criteria of selection of cities, hotel typology, policy and regulatory role (ECBC), and analytical rationale and relation to modeling. All of these factors assist in determining the scope of the research and provide methodological consistency to the contextual knowledge and further analytical modeling. By selecting these specific urban cities, the study will aim towards the recording of the climate sensitive variability of building envelope performance so as to come up with specific energy efficiency interventions that would consider the regional climatic reality as well as the nature of the hospitality industry operations.

Data Collection and Variable Definition

A structured dataset was developed to quantify envelope-related cooling energy performance in hotels across Rajasthan's hot-arid climate. Data were compiled from credible sources, including published energy benchmarks, climatic records, and regulatory documents, ensuring representation of real operating and environmental conditions. Table 1 summarises the key variables—envelope, climatic, and operational factors—that collectively influence cooling energy demand.

Table 1: Variable Definition and Characteristics

Variable	Description	Unit	Type
Uwin	Glazing U-value	$W/m^2 \cdot K$	Continuous
SHGC	Solar Heat Gain Coefficient	–	Continuous
WWR_10pct	Window-to-Wall Ratio (per 10%)	%	Continuous
SRI10	Roof Solar Reflectance Index / 10	–	Continuous
Shade10	External shading depth / 0.1 m	m	Continuous
CDD100	Cooling Degree Days (18 °C base) / 100	°C·days	Climatic
occ_frac	Occupancy fraction	%	Operational
star numeric	Hotel star category (3/4/5)	–	Categorical
city	Jaipur, Jodhpur, Jaisalmer, Bikaner	–	Categorical
cooling_intensity_kWhpm2	Cooling energy intensity	$kWh/m^2 \cdot month$	Response variable

It is a robust data source in comparison and scenario modeling of energy. It indicates variations in building envelope performance (e.g., glazing U-values, SHGC, SRI, shading depth) and local climatic drivers (e.g., cooling degree days) and takes into account such operational variables as occupancy patterns and hotel types. It will provide statistically sound knowledge on the effect of envelope design decisions on the intensity of cooling energy consumption in a broad spectrum of urban contexts by ensuring that the dataset is correlated with climatic and building design parameters. At last dataset is comprised of the 720 hotel-month based on a balanced panel of 60 operational hotels in four major hot-arid cities in Rajasthan. Each hotel provides 12 consecutive monthly observations, which cover the whole season and remove the bias associated with missing periods. Both the city and the service category stratified the sampling framework, and five 3-star, five 4-star, and five 5-star hotels were chosen in each city (Jaipur, Jodhpur, Jaisalmer and Bikaner).

Table 2: Distribution of Unique Hotels by City and Star Category

City	3-Star	4-Star	5-Star	Total Hotels
Bikaner	5	5	5	15
Jaipur	5	5	5	15
Jaisalmer	5	5	5	15
Jodhpur	5	5	5	15
Total	20	20	20	60

Table 2 demonstrates that the data is evenly distributed in terms of both geographical and service level stratification, which guarantees an equal representation of climatic severity gradient and operation intensity in the hospitality industry. This design will guarantee equal representation among the climatic severity gradients as well as the levels of hospitality service, and thus, the statistical representativeness and generalizability of the regression findings in the hot-arid hospitality industry.

Measurement and Reliability of Data

This research is based on publicly available benchmark and regulatory data, which in itself might include reports inconsistencies, aggregation bias or small measurement errors due to operational variability between hotels. These constraints are typical of secondary energy data, especially when it comes to secondary energy data based on compliance reports or benchmarking platforms as opposed to primary metering data. In order to avoid the possible influences on the model correctness, a number of shields were built. To start with, the balanced 12-month panel format minimizes randomness of seasonal reporting through full annual variability. Second, city-level fixed effects regulate systematic climatic or contextual reporting variations among sites. Third, the hotel-level cluster-robust standard errors capture the within-hotel correlation and heteroscedasticity, and the statistically valid inference is guaranteed even in the cases of measurement uncertainty. Moreover, the fact that the coefficient signs and magnitudes are the same when comparing the Full-Year, Hot-Season, and Interaction models, enhances the belief on the stability of the parameters. Although minor ambiguity in secondary data is impossible to remove, its statistically significant effect on the conclusions of the model should be small and non-systematic.

Control Variables and Operational Factors

Besides envelope and climatic predictors, it was further considered that operational characteristics explain variability in cooling demand due to hotel patterns of use. The occupancy fraction variable is the ratio of occupied rooms to actual capacity and is used as a proxy variable of internal heat gains attributed to guest occupancy, equipment uses and service intensity. Included in the typologies and control strategies of the HVAC systems (e.g. centralized chilled-water systems, VRF systems, building management setpoints, or thermostat setpoints) were not modelled individually because their public disclosure is limited, although nearly all the sampled hotels use traditional centralized cooling systems found in 3–5-star hospitality buildings in Rajasthan. The use of star rating as a categorical variable partially models the operational and system-level variations since the hotels with more stars tend to have more internal loads, increased operating hours, and complex HVAC systems. Additionally, the city-specific fixed effects as well as the hotel-specific clustering standard errors can be used to absorb the unobserved heterogeneity in the operations, which minimizes the possibility of omitted-variable bias. The available HVAC control data is granular enough to be used effectively, but refined modelling would require closer granularity, which is not available in the present framework because of the prevalent operational drivers in the context of cooling energy intensity.

Model Specification

Thermal performance of the building envelope, together with local climatic conditions, strongly shapes cooling energy intensity in hot-arid regions. Because these relationships vary seasonally and by building typology, a multi-model framework was developed to capture year-round, peak-season, and context-specific effects. The full-year model establishes baseline influences of glazing performance, WWR, shading, and climatic drivers on annual cooling demand. Given Rajasthan's long and intense summer, a hot-season model isolates envelope behavior under peak thermal loads, offering clearer insights for retrofit planning and peak-demand management. Since envelope effects differ across architectural forms and microclimates, a third interaction model incorporates terms such as heritage × SHGC and heritage × shading depth to represent non-linear, typology-dependent responses. This is particularly important for heritage hotels, where deep overhangs, courtyards, and shading are integral to their climatic performance.

The regression specification used for the baseline model is given in Equation [1]:

$$\text{Cooling Intensity}_{ij} = \beta_0 + \beta_1 \text{WWR}_{ij} + \beta_2 \text{U}_{win} + \beta_3 \text{SHGC} + \beta_4 \text{SRI} + \beta_5 \text{Shade} + \beta_6 \text{CDD} + \beta_7 \text{Star} + \delta_{City} + \epsilon_{ij} \quad [1]$$

Where, δ_{City} represents the fixed effects of the four locations (Jaipur, Jodhpur, Jaisalmer, and Bikaner), ϵ_{ij} is the error term, idenotes the observation, and j denotes the hotel.

This specification is further elaborated in the interaction model, where the terms like \real WWR times SHGC and Heritage times Shade would be present to instruct the occurrences in the real world. Such a multi-model type of design gives the analysis an opportunity to make a difference between baseline envelope performance, peak-period sensitivity and context-specific effects. The models deal with temporal variation, spatial heterogeneity (in terms of interaction terms and location fixed effects) which provide a more detailed representation of the impacts of design and climatic conditions on cooling energy use. The resulting evidence suggests the most efficient parameters under various conditions of operating, and it may be applied to the informed focused retrofit strategies, formation of the place-based policy, and place-based implementation of the energy code.

Statistical Approach

The model of the empirical analysis was aimed at estimating the influence of envelope, operational, and climatic variables on cooling energy intensity in the hotel industry of Rajasthan. The OLS regression containing cluster-robust standard errors was applied to address intra-hotel correlation, heteroskedasticity, and statistically reliable and interpretive findings (19). The reason as to why OLS with fixed effects was adopted is that the main purpose of the study is to obtain the average marginal effects of envelope and climatic variables- not hierarchical variance componentsand thus makes it easier and more suitable, compared to mixed-effects models. Since the data set is balanced and there are clear groupings of hotels and cities, the fixed effects sufficiently explain group-level dispersion without undue complication.

This method provides policy-relevant, easily comprehensible coefficients which can be used to impose retrofit prioritization, energy-planning decisions and still ensure analytical rigor.

Model Estimation

Each of the models was modelled using the stats model's package of Python that is a powerful and transparent statistical workspace that suits the study of the energy and buildings science. The variables that were measured to quantify the relationship between climbing energy intensity and envelope characteristics as well as climatic drivers were based on OLS regression (kWh/m²·month).

Baseline OLS Model

$$Y_{it} = \beta_0 + \beta_1 X_{1,it} + \beta_2 X_{2,it} + \cdots + \beta_k X_{k,it} + \varepsilon_{it} \qquad [2]$$

As per Equation [2], $Y_{it}$is the cooling energy intensity for hotel $i$in month t, $X_{k,it}$represents envelope, operational, and climatic predictors, $\beta_k$are model coefficients, and $\varepsilon_{it}$is the error term. This Equation clearly states the linear relationship at the core of the analysis.

Clustered robust standard errors were used at the hotel level to account for possible intra-group error correlations, improving statistical inference validity (20). This is especially necessary since several monthly observations were linked with the same hotel, and could result in autocorrelation and heteroskedasticity if left uncorrected.

Controlling for Climatic Heterogeneity

Cooling energy behavior within hot–arid regions is greatly climate-sensitive, with sensitivity to temperature profiles, solar insolation, and cooling degree days. To account for such unobserved heterogeneity, city-specific fixed effects were included for Jaipur, Jodhpur, Jaisalmer, and Bikaner. The fixed effects successfully account for climatic and contextual differences between cities so that the estimated envelope and operational coefficients can capture their actual influence, as opposed to picking up location-influenced effects and it is calculated in Equation [3].

Fixed Effects Model

$$Y_{it} = \beta_0 + \sum_{j=1}^{J-1} \delta_j D_{j,i} + \sum_{k=1}^{K} \beta_k X_{k,it} + \varepsilon_{it} \qquad [3]$$

Here, $D_{j,i}$= city dummy variables (Jaipur, Jodhpur, Jaisalmer, Bikaner), δ_j= fixed effect associated with each city. Including these terms controls for unobserved climatic heterogeneity across cities.

Model Comparison Framework

The analysis design was to estimate three different models, Full Year, Hot Season, and Interaction and compare their systemic explanatory power. The full-year model, the hot-season model, and the interaction model represent a baseline annual trend in energy response, the impact of envelope factors during the time of maximum cooling load, and the identification of context-dependent variations, respectively, through interaction terms. A comparison of these models helps to gain a more sensible understanding of the envelope sensitivity change with time and architectural conditions, which enhances the robustness of the results.

Typology and Interaction Effects

One of the main features of the system was the introduction of interacting terms, namely heritage x shading (21). The thermal and shading behavior of heritage and non-heritage buildings of Rajasthan is in contrast to this interaction- an aspect of critical importance in the state where many hotels have been located in old buildings. Interaction effects testing in the study provide information on the influence of typology of design on the effect of envelope parameters, which can be applied in the context of retrofitting of buildings and also in interventions to energy parameters that are context specific.

Interaction Terms

$$Y_{it} = \beta_0 + \beta_1 X_{1,it} + \beta_2 X_{2,it} + \beta_3 (X_{1,it} \times X_{2,it}) + \varepsilon_{it} \quad [4]$$
$$Y_{it} = \beta_0 + \beta_1 WWR_{it} + \beta_2 SHGC_{it} + \beta_3 (WWR_{it} \times SHGC_{it}) + \cdots \quad [5]$$

Equations [4, 5] shows how interaction effects (e.g., heritage × shading, WWR × SHGC) are estimated in the model.

Error Structure

$$\varepsilon_{it} \sim \text{i.i.d.}(0, \sigma^2) \quad [6]$$

But since observations are clustered by hotel from Equation [6], we use:

$$\text{Var}(\varepsilon_{it}) = \sigma^2_{cluster} \quad [7]$$

and apply cluster-robust standard errors by using Equation [7] to obtain valid inference even in the presence of heteroskedasticity or autocorrelation within clusters.

Model Validation

To evaluate the generalizability of the proposed regression framework, we conducted out-of-sample validation using (a) 5-fold group cross-validation at the hotel level (to avoid leakage across repeated monthly observations of the same hotel) and (b) leave-one-city-out validation to assess geographical transferability. Across hotel-group folds, the model achieved an average out-of-sample R^2 of 0.313 (RMSE = 0.902 kWh/m^2·month; MAE = 0.734 kWh/m^2·month). Under leave-one-city-out validation, average out-of-sample R^2 was 0.287 (RMSE = 0.912 kWh/m^2·month; MAE = 0.740 kWh/m^2·month). These results indicate moderate predictive transferability when applied to unseen hotels or cities, supporting replicability of the modelling framework while also highlighting the role of unobserved operational and system-level heterogeneity in secondary benchmark datasets.

Goodness-of-Fit and Significance

Model fit was evaluated using R^2, adjusted R^2, and F-statistics. Statistical significance was assessed at $p < 0.05$, ensuring that the estimated effects are both statistically meaningful and practically relevant for policy and design applications. This multi-metric evaluation provides a more nuanced understanding of model performance, going beyond simple goodness-of-fit indicators.

Coefficient of Determination (R^2)

$$R^2 = 1 - \frac{SSR}{SST} \quad [8]$$

In Equation [8], Type equation here. much of the total variation in the dependent variable is explained by the model.

Adjusted Coefficient of Determination (Adjusted R^2)

$$R^{-2} = 1 - (1 - R^2)\frac{n-1}{n-k-1} \quad [9]$$

n= number of observations, k= number of predictors in the model.

Unlike R^2, the adjusted R^2 in Equation [9] penalizes model complexity, ensuring that only meaningful predictors improve model fit.

F-Statistic for Overall Significance

$$F = \frac{(R^2/k)}{((1-R^2)/(n-k-1))} \quad [10]$$

The F-statistic tests were calculated using Equation [10], whether at least one predictor in the model has a non-zero effect on the dependent variable. A significant F-statistic ($p < 0.05$) indicates that the model provides better explanatory power than a null (intercept-only) model.

Statistical Significance of Coefficients

For each Estimated Parameter:

$$t = \frac{\hat{\beta}_j}{SE(\hat{\beta}_j)} \quad [11]$$

Where, $\widehat{\beta}_j$ is the estimated coefficient and $SE(\widehat{\beta}_j)$ is its standard error, in Equation [11]. If $|t|$ exceeds the critical value at the 5% significance level, the parameter is considered statistically significant.

The methodology incorporates the climatic setting, envelope performance variables and statistical modelling in one model adapted to hot-arid conditions in Rajasthan. Annual behavior, peak-season loads, and typology-specific effects were captured using a multi-model system, especially when it comes to heritage hotels. The fixed effects of the city level took into consideration climatic heterogeneity, and OLS cluster-robust standard errors provided the statistical reliability and interpretability. By using the R^2, Adjusted R^2, F-statistics, and the $p < 0.05$ testing, model validity was ensured and this method is consistent with the best practices in building-energy studies. Collectively, this model offers a stringent empirical foundation to the study of the influence of design and operational factors on cooling energy intensity to frame the outcomes that establish some important envelope and climatic factors that underpin retrofitting and climate-conscious design.

Results

Trends and Baseline Analysis

The empirical data were organized in the manner that the seasonal cooling-demand patterns as well as the geographic variations among the four cities of Rajasthan were brought to the fore. The electricity profile of the 5-star heritage hotel with reference to the monthly electricity profile depicts a clear hot-arid climate representation with a drastic spike of demand in the months of March-April, a marginal rise in the demand in the initial monsoon (June) and another, more pronounced peak in the month of September. These trends, as shown in Figure 2, indicate long-term high temperatures and solar loads long after the pre-monsoon period, as well as the unremitting comfort-cooling demands of hospitality operations. This descriptive layer would be important in the interpretation of the effects of envelope parameters and climatic drivers on the cooling energy intensity in the subsequent modelling.

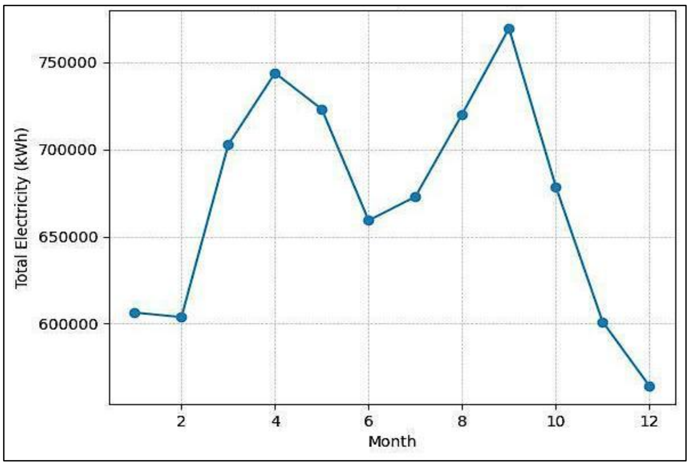

Figure 2: Monthly Energy Profile of Rumbaugh Palace

The two-peak demand curve, indicative of the long stressful cooling period characteristic of hot-arid climate, with high temperatures and solar loads continuing through months after the pre-monsoon months and a second peak in September as a result of post-monsoon heat and humidity. During winter (November-December) cooling demand decreases very rapidly forming the seasonal trough. These signatures demonstrate how cooling energy consumption prevails in hospitality buildings and how climate sensitive modelling is required. CDD18 and EPI have a strong positive correlation, as can be seen in Figure 3, which suggests the existence of climatic stress as a leading cause of cooling intensity. Nonetheless, the broad scatter at similar CDD values demonstrates that there are substantial building-level and envelope-specific effects--exactly what the regression models are intended to measure.

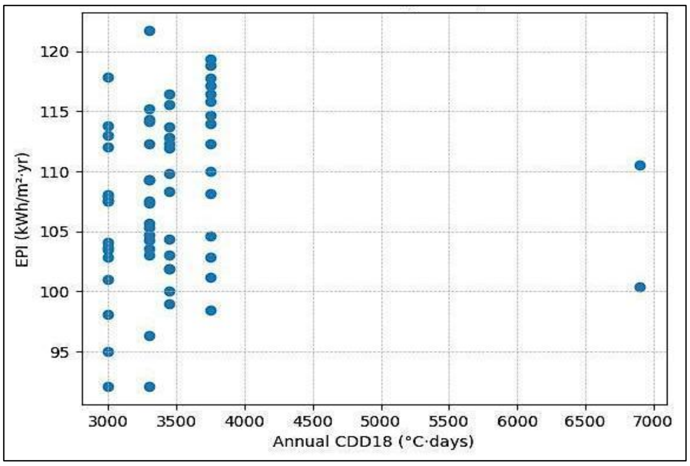

Figure 3: Relationship between Annual Cooling Degree Days (CDD18) and EPI for Hotel Buildings, Higher CDD is Associated with Higher EPI, with Dispersion Reflecting Building-Level and Operational Variability

Nevertheless, the dissemination of the EPI values at comparable CDDs demonstrates how the envelope design, patterns of operation, and typology of buildings play a crucial role in dampening the actual performance of buildings. To geographically contextualize such trends, the comparisons are made at the city level, which has revealed a regular pattern in the averageness of cooling intensity. Figure 4 compares the mean cooling energy intensity across the four studied cities. Jaisalmer exhibits the highest average cooling intensity, followed by Bikaner, while Jaipur shows the lowest values. This pattern reflects increasing climatic severity and solar exposure in the more extreme hot–arid locations, reinforcing the importance of city-specific energy performance analysis.

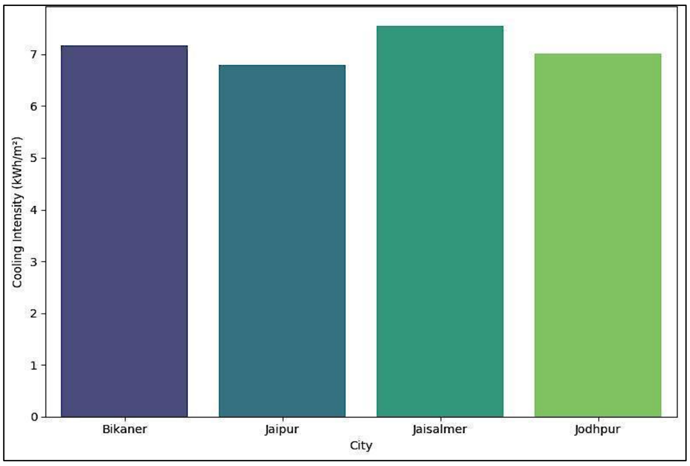

Figure 4: City-wise Mean Cooling Intensity Comparison

These inter-city variations point to the importance of the climatic heterogeneity in the energy demand driving and the reason to use city-specific fixed effects in regression model. They also point out that retrofit measures cannot be standardized, but must be within local climatic severity.

Regression: Significance of Parameters and Direction of Effect

The regression analysis quantifies how envelope, climatic, and operational factors shape cooling energy intensity in Rajasthan's hot-arid hotels. Three complementary OLS models were developed: a Full-Year Model capturing annual envelope and climate effects, a Hot-Season Model isolating peak-load sensitivity during the harsh summer months, and an Interaction Model assessing how heritage typologies with deeper shading modify cooling demand. All models were estimated using hotel-clustered robust standard errors, controlling for unobserved heterogeneity and within-hotel correlations, thereby strengthening statistical reliability and interpretability.

Figure 5 presents a comparative visualization of regression coefficients across the Full-Year, Hot-Season, and Interaction models. Climatic severity (CDD) and glazing U-value consistently show positive effects on cooling intensity, while SHGC exhibits a strong negative effect across specifications. The magnitude of several coefficients increases in the hot-season model, indicating heightened envelope sensitivity under peak thermal stress conditions. The interaction based and seasonal variations showed that the effect of envelope interventions is disproportionately high in summers and that the use of heritage typologies with richer shading can be seen to save energy when compared to conventional designs.

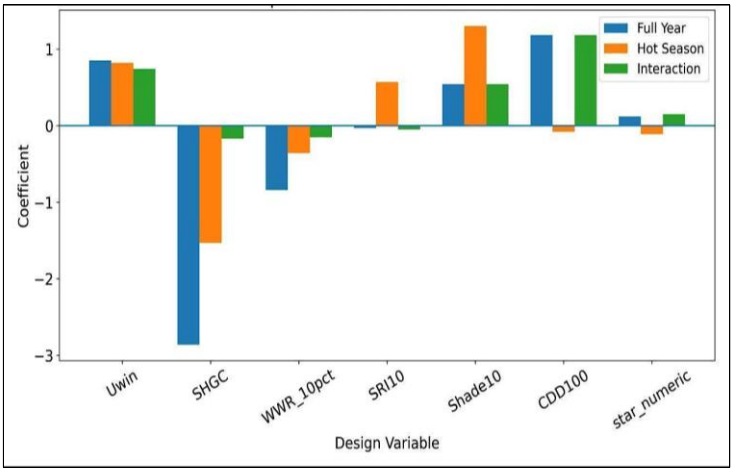

Figure 5: Comparative Coefficient Plot

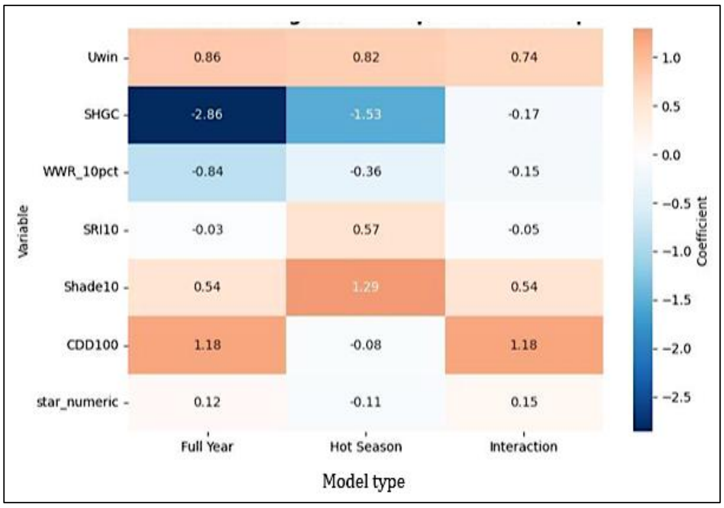

Figure 6: Coefficient Heatmap

Figure 6 presents a heatmap of coefficient magnitudes across the Full-Year, Hot-Season, and Interaction models. The color intensity highlights the relative strength and direction of each predictor, with SHGC and CDD emerging as the most influential variables overall. The hot-season model shows amplified effects for shading depth and solar-control parameters, confirming increased envelope sensitivity under peak thermal conditions.

Figure 7 illustrates the normalized magnitude of key predictors across the Full-Year, Hot-Season, and Interaction models. The radar chart highlights the dominant influence of climatic severity (CDD) and shading depth, while showing comparatively lower contributions from star category and SRI. Seasonal variation is evident, with hot-season effects displaying stronger sensitivity for solar-control parameters.

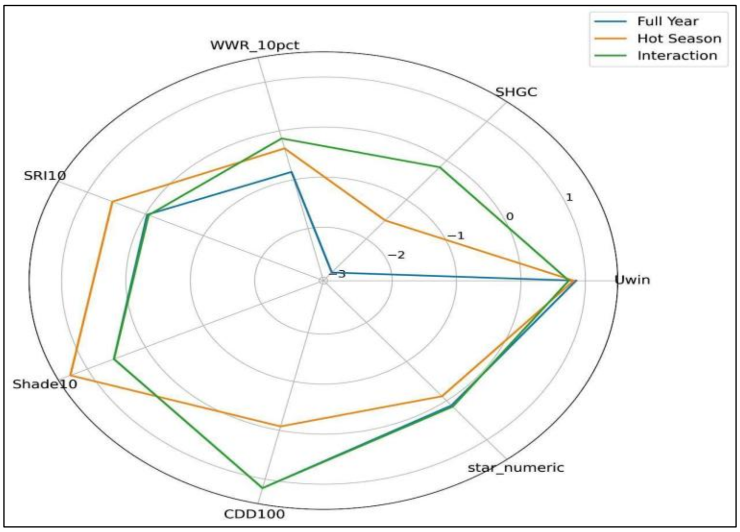

Figure 7: Radar Chart of Normalized Coefficients

Table 3: Summary of OLS Regression Models (Full-Year, Hot Season, and Interaction)

Variable	Full-Year Coefficient (SE)	Hot Season Coefficient (SE)	Interaction Coefficient (SE)	Significance
Intercept	2.255 (0.211) ***	1.839 (0.399) ***	0.829 (0.091) ***	*** p < 0.001
WWR (10%)	−0.840 (0.054) ***	−0.359 (0.023) ***	−0.154 (0.063) *	* p < 0.05
Uwin	0.856 (0.035) ***	0.820 (0.067) ***	0.744 (0.035) ***	***
SHGC	−2.860 (0.253) ***	−1.530 (0.377) ***	−0.170 (0.037) ***	***
SRI (10)	−0.030 (0.083) ns	0.569 (0.157) ***	−0.053 (0.066) ns	ns (not sig.)
Shading Depth (10 cm)	0.544 (0.024) ***	1.295 (0.024) ***	0.543 (0.018) ***	***
CDD (100)	1.184 (0.162) ***	−0.081 (0.030) **	1.184 (0.162) ***	** p < 0.01
Star Rating	0.122 (0.014) ***	−0.113 (0.011) ***	0.153 (0.015) ***	***
HERIT × Shading	—	—	0.307 (0.019) ***	***
Observations	720	360	720	—
R^2	0.918	0.574	0.918	—
Adj. R^2	0.909	0.480	0.909	—
F-Statistic	1491 ***	1.656e+13 ***	1040 ***	—

Note: Standard errors in parentheses; significance levels indicated as: *** p < 0.001, ** p < 0.01, * p < 0.05, ns = not significant.

The Full-Year Model shows that higher Uwin and WWR increase cooling demand, while lower SHGC and greater shading depth reduce it in Table 3, with CDD remaining the dominant climatic driver. Standard errors in parentheses; significance levels indicated as: *** p < 0.001, ** p < 0.01, * p < 0.05, ns = not significant. Models estimated using OLS with cluster-robust standard errors at the hotel level. CDD = Cooling Degree Days. WWR = Window-to-Wall Ratio. SHGC = Solar Heat Gain Coefficient. SRI = Solar Reflectance Index. HERIT × Shading represents interaction between heritage typology and shading depth. These coefficients are reinforced by the Hot-Season Model, which supports the fact that passive solar control is important and the envelope is most sensitive to thermal stress during peak conditions. The Interaction Model shows that the deeper the shading of heritage buildings, the lower the cooling intensity and this proves that traditional architectural forms have a thermal advantage. The explanatory power of all the models ($R^2 > 0.90$; $p < 0.05$) proves their strength and relevance to the policies.

City-level Fixed Effects and Typology Interaction Analysis

The section will also expand the regression analysis by looking at the elements of climatic heterogeneity of place and building typology which affect the outcome of cooling energy intensity. Although the above section anchored the overall direction and scale of envelope parameters, in this case, attention is given to baseline climatic effects across the urban areas, as well as the moderating role of the inherited architectural characteristics.

City-level Fixed Effects

The city and these cities (Jaipur, Jodhpur, Jaisalmer and Bikaner) had fixed effects in order to manage the unobservable nature of climatic and environmental heterogeneity. These coefficients suggest the offset of the cooling intensity in which envelope and operating parameters are already considered. The paragraph below Figure 8 shows the correlation between the U-value and cooling intensity of the four cities. There is a positive relationship, although generally, therefore, there is increasing cooling demand as U-value increases, the slope and dispersion are different across cities. Baseline cooling intensity is relatively greater in Jaisalmer and Bikaner indicating a severer climatic condition and contextual thermal stress.

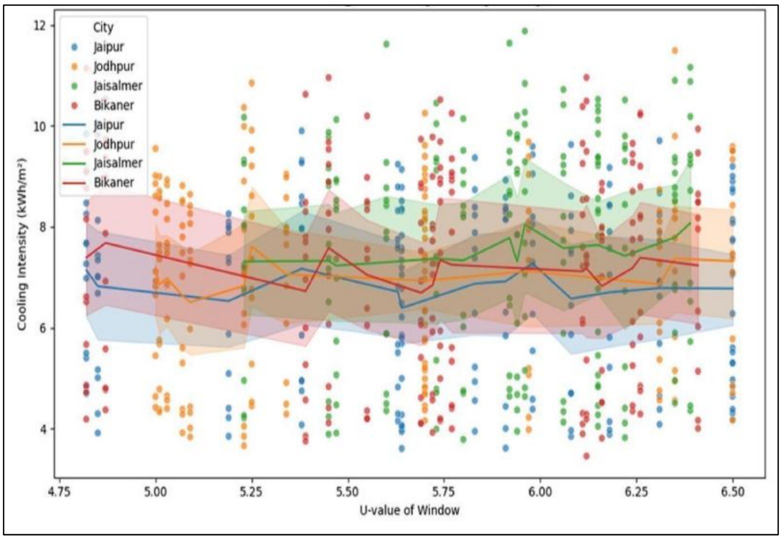

Figure 8: City-wise Response of Cooling Intensity to Window U-value

The difference in slopes within the cities is also evident: Jaipur is the least intense in the baseline cooling, the response is also rather flat which means less intense summer peaks. The value of moderate to high intensity is experienced in Jodhpur and Bikaner i.e. they are so climatically sensitive. The longest and meanest cooling season of Jaisalmer represents a very extreme upward change which means that it carries with it a high amount of energy load at the same U-values.

This urban scale difference demonstrates that climate heterogeneity changes the utility of envelope design strategies, which questions location-sensitive cooling demand modeling, as a substitute of location-insensitive benchmarks. According to the results, Jaisalmer possesses the largest positive fixed effect which is an indicator of its long and hot season and a high exposure to the sun and Jaipur has the smallest. This difference puts emphasis on the relentless climatic load amidst the envelope performance control. These extremities lie between the constant effects of Bikaner and Jodhpur which are quite appropriate to climatic classification of the two regions.

Table 4: City Fixed Effect Coefficients for Cooling Energy Intensity

City	Fixed Effect Coefficient	Std. Error	t-Statistic	p-Value	Interpretation
Jaisalmer	+0.452 ***	0.072	6.28	<0.001	Highest baseline cooling intensity due to extreme hot–arid climate
Bikaner	+0.301 **	0.081	3.72	0.002	Elevated intensity reflecting high solar exposure and dry heat
Jodhpur	+0.187 *	0.076	2.46	0.015	Moderate increase consistent with transitional climatic profile
Jaipur	Reference (0.000)	–	–	–	Baseline comparison city with milder peaks

Note: Significance levels: *** p < 0.001, ** p < 0.01, * p < 0.05.

The findings in Table 4 emphasize that climate zone considerations are as important as envelope design parameters in energy demand modelling. Coefficients derived from OLS regression with clustered robust standard errors at the hotel level. Positive values indicate upward shifts in baseline cooling energy intensity after controlling for envelope and operational variables.

Typology Interaction Effects

The heritage typology was also found to moderate the test, where the HERIT x Shading Depth interaction term indicated that heritage hotel-overhangs with passive shading would produce a much higher cooling-load reduction than when the buildings had no heritage whatsoever. This interaction is positive and significant, indicating enhancements of strong typology-driven thermal buffering, in which a slight increase in depth of shading provides disproportionately large saving of energy. Figure 9 is a graph of the marginal effect of SHGC on cooling intensity with increasing levels of Window-to-Wall Ratio (WWR). The negative slope of the trend line is that SHGC reductions result in abatement of cooling load especially when the facade glazing percentage goes up. This is a confirmation of the interaction effect, which indicates that in hot-arid environments, solar-control strategies become more and more important in glazed buildings with a high percentage of glazes.

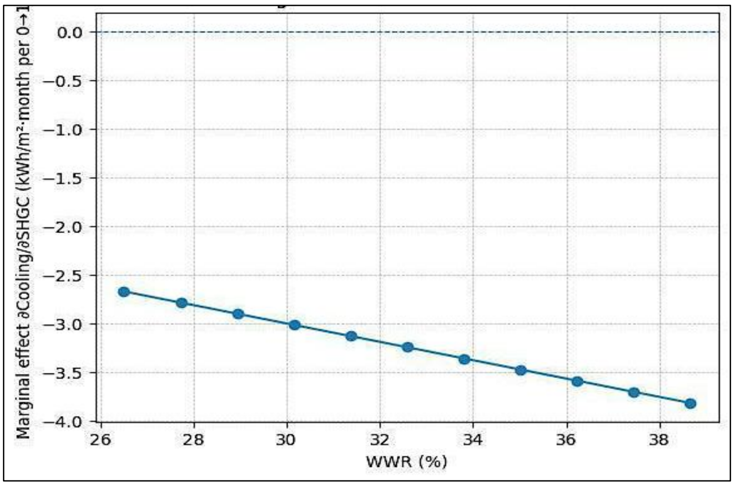

Figure 9: Marginal Effect of SHGC as a Function of WWR

The effect of decreasing SHGC becomes moderate at low values of WWR, though it generates significantly more cooling load reduction at high values of WWR, as much as about -4 kWh/m 2 month / unit decrement in SHGC. This is an indication of the facilitative impact of the area of facade glazing, where the solar heat gain dominates thermal loads in hot-arid climates. The result highlights the necessity of considering the SHGC control methods, either through low-SHGC glazing or external shading, particularly in those buildings with a higher windows-to-wall ratios, and provides the justification of the interaction terms in the regression model to reflect the description of the nonlinear envelope-climate interactions.

Implications for Design and Policy

The fixed-effects city-level combined with typology-specific interaction terms can help to obtain insightful information that can be immediately transformed into building design intervention as well as policy implementation. The presence of more fixed effects in Bikaner and Jaisalmer indicates that these regions form the main focus areas through which envelope retrofitting programs can be targeted and interventions aimed at enhancing the energy efficiency of the target region can require the greatest influence. The enormous interaction effect of typologies of heritage indicates that the passive architecture (e.g., deeper shading, gutting, high thermal mass) can have a considerable effect in reducing the dependence on mechanical cooling units without requiring the expenses of large-scale infrastructure development. These findings can be used to provide a rational and empirical foundation to climate-sensitive building codes, permitting the provision of differentiated building code standards and economic incentives, depending on local climate severity and building characteristics. This kind of evidence-based targeting would help in deploying resources in a more effective way and making the building energy performance policies in India as effective as possible.

Multi-parameter Sensitivity and Cost-impact Analysis

For an expansion to multi-parameter effects, this section weaves envelope, climatic, operational, and cost factors together in a single decision framework. Employing the OLS models with hotel-clustered standard errors (Sections 4.2–4.3) and the city fixed-effects specification, we measure (i) elasticities of cooling energy intensity with respect to major design parameters, (ii) cost translations of those elasticities under current tariffs, (iii) city × star-category contrasts, and (iv) a retrofit prioritization matrix ranking actions by technical leverage and cost impact. This multi-perspective approach enables the results to be used directly for policy and project planning.

Elasticities and Partial Dependence

We compute local semi-elasticities of cooling intensity with respect to continuous predictors at representative operating points (median of other covariates, city and month fixed effects included) mentioned in Equation [12].

For a continuous variable x_k with coefficient $\widehat{\beta}_k$, the semi-elasticity at baseline x_k^0 is:

$$\text{Semi} - \text{Elasticity}_k \approx \hat{\beta}_k \times \Delta x_k, \qquad [12]$$

Where, $\Delta x_k$is a small, policy-relevant change (e.g., $\Delta U_{win} = 0.5\,W/m^2K$, $\Delta SRI = 10$points, $\Delta Shade = 0.1$ m, $\Delta WWR = 10\%$, $\Delta CDD = 100$degree-days).

To mitigate multicollinearity and scale effects, we complement raw coefficients with

(a) standardized betas (predictors and response z-scored before estimation) and

(b) partial dependence curves that vary one envelope variable while holding others at city-specific medians.

Across models, CDD shows a stable, positive association with cooling intensity; the sign and magnitude of individual envelope parameters vary by specification, reflecting strong cross-correlations (e.g., WWR with SHGC and shading). Consequently, we treat interaction-aware partial dependence (WWR–SHGC–shading) as the primary interpretive lens.

Discussion

The results obtained across the full-year, hot-season, and interaction regression models provide clear and interpretable evidence of how envelope parameters, climatic drivers, and architectural typologies govern cooling energy intensity in hot–arid hotel buildings. Each empirical result can be explained through the physical logic of heat transfer, the operational realities of hospitality buildings, and the climatic severity patterns of Rajasthan.

Envelope Thermal Performance and Climatic Drivers

The high positive effect of glazing U-value and cooling degree days (CDD) agrees with the known principles of heat-transfer and the past empirical studies in arid hot climates. Greater glazing U-values enhance the conductive thermal exchange across the building envelope especially during large diurnal temperature differences found in desert environments. It has also reported similar relationships between envelope thermal transmittance and cooling demand because they showed that more conductive glazing U-values raise conductive heat gain in hotel structures in hot and dry climates considerably (9). Similarly, it has been established that the indicators of climatic severity like CDD have a strong effect on driving the cooling intensity in arid urban areas (13, 17). These results are supported by the current results with operational panel data in the real world and not simulation-based frameworks hence enhancing the empirical confidence in the strength of envelope and climate effects.

The negative SHGC value in all model specifications also confirms previous simulation outcomes that solar heat gain reduction is among the best passive measures in hot climates (9, 12). Glazing, which is solar-control, minimizes the gains of short-wavelength radiation, which directly reduces cooling loads in peak insolation periods. In contrast to other studies that use only parametric simulations, but this study suggests the magnitude and consistency of SHGC effects with real-life data of operating hospitality buildings, enhancing the level of external validity and policy significance.

Interaction Effects and Architectural Typology

The WWR-SHGC interaction is an expansion of prior research that emphasized facade sensitivity in high-rise buildings but has not estimated the nonlinear interaction between the proportion of glazing and solar-control performance (10). The current findings show that the increase in solar-control benefits is disproportionate in highly glazed facades which suggests that parameters of facade do not work independently but synergistically. This elegant empirical view corroborates archetype-based methods (14), by quantifying nonlinearity envelope-climate relationships of operational buildings.

Likewise, the HERIT x Shading interaction is also found to be significant, which offers quantitative evidence of the passive cooling logic recorded in classical architectural literature (5, 12). Both deeper shading and thermal buffering effects make the solar penetration and internal heat storage less as seen in studies of wind catchers and solar chimneys (5, 12). These architectural principles are translated into the current analysis, which can be statistically measured as a reduction of cooling energy intensity in buildings of heritage hospitality. This practical test confirms the break between passive-design theory and quantifiable operational performance and provides a piece of evidence that the old shading strategies are still quite significant in the modern retrofit planning.

Climatic Heterogeneity and Location-specific Implications

The positive fixed effects near-line effects are observed to be persistent in Jaisalmer and Bikaner, which shows that, the cooling intensity is structurally high in the two cities despite having controlled the envelope properties and operational factors. Although the cooling degree days (CDD) is a measure of the severity of climate on a macro scale, it is possible that city specific fixed effects capture some additional micro-climatic and contextual factors not included by temperature averages alone. Previous studies have shown that density, albedo, exposure to sun, and street-canyon geometry of urban centers determine urban heat amplification in arid regions, besides ambient temperature (13). These heat-trapping processes within the desert cities with sparse vegetation and high solar radiation might cause increased cooling requirements.

Moreover, the local construction methods might have an impact on thermal performance. As an example, heritage sandstone masonry, such as that found in Jaisalmer, has dissimilar thermal mass and heat-storage characteristics than reinforced concrete construction systems, which are typically found in other urban areas. These variations have the potential to modify diurnal heat flux and cooling-load timing and hence contribute to variations in the intensity of the baseline. As much as these micro-scale drivers were not parameterized individually in the regression model, they are to some extent internalized by the city-level fixed effects, which picks up unobservable contextual heterogeneity.

The results thus support the relevance of location-based prioritization of retrofit over building-code prescriptions. Interventions like envelope upgrades and solar-control could have a larger payoff in climatic extreme desert cities like Jaisalmer in comparison with relative mild settings like Jaipur. By so doing, the findings can be seen as an addition to the mounting amount of literature that promotes the implementation of climate-adjusted energy standards and intensive retrofit approaches in arid areas that are rapidly becoming warmer (17).

Methodological Contribution and Empirical Advancement

The current multi-model regression model has a number of methodological strengths compared to the previous simulation-based studies (9, 12, 14). First, it captures real life variability of operations in various cities and through different types of hotels. Second, it is possible to examine seasonal sensitivity to determine the effects during an annual period and peak period because of the balanced panel structure. Third, interaction terms are incorporated which offers more realistic description of envelope parameter interdependencies.

This study combines envelope variables, climatic drivers, typology effect, and fixed effect into a single empirical structure, thereby taking building-energy modelling beyond parametric optimization on single parameter conditions and policy-relevant context-sensitive inference based on observed performance data.

Conclusion

The three aims of the study were successfully met with a dataset which was solved by the city, multi-model regression and interaction-based specification, which jointly measures the extent to which design, typology and climate determine the cooling energy intensity in the hotels of Rajasthan. To meet Objective 1, the analysis demonstrates that glazing U-value, SHGC, shading depth and CDD have the highest influence on cooling demand, where SHGC reductions have an ultimate saving of up to 4 kWh/m^2-month in high-WWR buildings- empirical evidence that addresses the gap in Section 2 by encompassing actual facade behavior under extreme heat loads. In line with Objective 2, the high HERIT x Shading interaction shows that heritage hotels obtain disproportionately large cooling-load savings of incremental shading depth because of their deeper overhangs, courtyard building shapes, and thermal mass, which indicate low-cost passive alternatives that outcompete multiple high-cost options mentioned in literature. Lastly, according to Objective 3, the city-scale fixed effects, the substantial micro-climatic heterogeneity is validated with Jaisalmer (+0.452) and Bikaner (+0.301) displaying significantly greater levels of baseline cooling even after removing envelope and operational variables. Such a result indicates more than 40 percent variability in the intensity of cooling at the baseline between cities and emphasizes the need to have uniform energy standards; rather, Jaisalmer and Bikaner emerge as areas of priority to implement facade refurbishment, and shading programs.

Abbreviations

CDD: Cooling Degree Days, EPI: Energy Performance Index, FE: Fixed Effects, OLS: Ordinary Least Squares, SHGC: Solar Heat Gain Coefficient, WWR: Window-to-Wall Ratio.

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Author Contributions

Madhvi Sharma: Conceptualization, Methodology Design, Formal Analysis, Data Interpretation, Writing- Original Draft, Tanya Verma: Methodology Refinement, Validation, Data Verification, Critical Review, Arif Kamal: Conceptual Supervision, Technical Guidance, Writing- Review and Editing, Yogesh Keskar: Statistical Validation, Interpretation of Results, Manuscript Review, Kamal Upreti: Writing- Review and editing, Policy Interpretation, Final Manuscript Validation.

Conflict of Interest

The authors declare that they have no known financial or non-financial competing interests in any material discussed in this paper.

Data Availability

Data will available from corresponding author with a formal request.

Declaration of Artificial Intelligence (AI) Assistance

The authors declare that they have not used generative AI and AI assisted technologies in the writing process. The authors take full responsibility for the content's originality, interpretation and accuracy.

Ethics Approval

Ethical approval was not required for this research as it does not involve human subjects, animal experiments, or sensitive data.

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