Published by Avanti Publishers

International Journal of Architectural Engineering Technology

ISSN (online): 2409-9821

Optimizing Urban Layout for Solar Mitigation and Microclimate Regulation in Hot-Arid Coastal Resorts: A Parametric Simulation Study

Ruwaa Bahgat[1], Rabee M. Reffat[2,*] and Shawkat L. Elkady[1]

[1]*Architecture Department, Faculty of Engineering, Assiut University, Assiut, Egypt*

[2]*Department of Architecture and Built Environment, University of Nottingham Ningbo China, Ningbo, China*

ARTICLE INFO

Article Type: Research Article

Academic Editor: Eric M. Lui

Keywords:
Urban morphology
Hot-arid architecture
Microclimate regulation
Solar radiation mitigation
Sustainable tourism resorts

Timeline:
Received: December 18, 2025
Accepted: February 19, 2026
Published: March 10, 2026

Citation: Bahgat R, Reffat RM, Elkady SL. Optimizing urban layout for solar mitigation and microclimate regulation in hot-arid coastal resorts: A parametric simulation study. Int J Archit Eng Technol. 2026; 13(1): 1-20.

DOI: https://doi.org/10.15377/2409-9821.2026.13.1

ABSTRACT

The rapid expansion of tourism infrastructure in hot-arid coastal regions exacerbates energy demands and environmental stress, yet evidence-based urban design guidelines for low-density resorts remain underdeveloped. This study investigates the influence of urban layout design (ULD) on façade solar exposure and microclimate regulation, using Egypt's Red Sea coast as a case study. Its purpose is to identify morphological strategies that reduce solar heat gain, lower cooling energy demand, and enhance outdoor thermal comfort while facilitating renewable energy integration.

A systematic parametric approach was employed, using TownScope-3 to generate and simulate 252 urban layout scenarios. Key urban form parameters—including open-space ratios, building orientation, canyon aspect ratios, and building distribution—were varied to evaluate their effects on façade-level solar radiation. Statistical analyses established robust correlations between morphology and solar mitigation outcomes.

Findings demonstrate that urban morphology is a decisive determinant of environmental performance. East-West linear layouts reduced annual façade solar irradiation by up to 29%, while compact, vegetated U-shaped clusters achieved reductions of up to 48%. Based on established correlations reported in the literature, these solar reductions correspond to estimated cooling energy savings of 23–32% and significant improvements in outdoor thermal comfort. Furthermore, by lowering ambient thermal loads, these passive strategies enhance the operational efficiency and feasibility of photovoltaic (PV) systems, positioning urban layout as a dual passive-active sustainability lever.

This research provides a context-specific, parametric framework for linking urban form optimization directly to energy and environmental performance in coastal resorts. It offers evidence-based morphological guidelines for developers and planners to reduce operational costs and improve climatic habitability. The strategies support climate adaptation and key Sustainable Development Goals (SDGs 7, 11, and 13), reinforcing the tourism sector's role in sustainable development.

*Corresponding Author
Email: rabee.reffat@nottingham.edu.cn
Tel: +(86) 15958248500

1. Introduction

Climate change and rapid tourism growth are intensifying energy demand and carbon emissions in coastal regions, particularly in hot-arid climates where cooling dominates building energy use [1, 2]. The tourism sector contributes significantly to greenhouse gas emissions, with coastal resorts emerging as especially vulnerable due to heavy reliance on energy-intensive cooling and exposure to extreme climatic conditions [3, 4]. As resort development accelerates globally, sustainable design strategies that integrate passive energy savings and renewable energy generation are critical to meeting decarbonization goals.

Urban layout design (ULD) is a decisive determinant of solar exposure, shading, and airflow, directly shaping cooling energy demand and the feasibility of renewable energy integration. Research demonstrates that compact planning, orientation, and natural ventilation can mitigate urban heat islands and reduce building energy loads [5-8]. However, this work has largely focused on dense urban morphologies in temperate or humid climates. In contrast, low-density, waterfront resorts in hot-arid zones remain underexplored, despite their distinctive spatial characteristics and growing global importance.

Such resorts, exemplified by those along Egypt's Red Sea coast, present unique energy challenges. Dispersed low-rise structures, extensive open spaces, and reflective surfaces like seawater intensify solar gains and diminish shading [9-11]. Water bodies can reflect 50–80% of incident solar radiation, amplifying façade-level heat loads [12, 13]. Furthermore, design priorities emphasizing scenic views often result in elongated or radial building patterns that increase solar exposure [14, 15], reducing the applicability of compact, shade-dense strategies effective in high-density contexts [16]. Consequently, conventional urban heat mitigation models are not directly transferable to these low-density, view-oriented settings [4, 17]. Recent research underscores the importance of tailoring solar-responsive urban form strategies to local climatic and morphological conditions [3, 18], yet systematic evidence for hot-arid waterfront resorts remains scarce.

This study addresses this gap by systematically evaluating the role of ULD features in mitigating solar radiation in hot-arid coastal resorts. Through parametric simulation of 252 layout alternatives for Egypt's Red Sea coast, we pursue the following research questions:

1. How do key urban layout parameters—including building orientation, compactness, open-space ratios, and canyon geometry—influence façade-level solar exposure in low-density waterfront resorts?
2. Which morphological configurations are most effective in reducing annual solar irradiation, and what is the magnitude of achievable reduction?
3. What are the indicative implications of these solar mitigation outcomes for cooling energy demand and renewable energy system performance?

By answering these questions, this research provides evidence-based, context-specific guidelines to inform climate-responsive resort planning, contributing to sustainable development goals (SDGs 7, 11, and 13).

The structure of this paper is organized as follows: Section 2 provides a review of related work; Section 3 details the research methodology; Section 4 presents the results; Section 5 offers a discussion of the findings; and Section 6 concludes the study.

2. Review of Related Work

2.1. Urban Morphology and Solar-Energy Performance

Urban morphology is a critical determinant of energy performance by shaping solar exposure, shading, and natural ventilation [19-22]. In dense urban environments, compact building arrangements can reduce façade exposure through mutual shading [23, 24]. However, this compactness can also restrict natural ventilation and promote heat retention [25-30]. Building orientation is central to maximizing solar availability and enhancing airflow [31-35], and forms like linear and courtyard layouts can effectively reduce solar exposure in hot climates [36-39]. These interrelationships are well-established in research on temperate, high-density settings [40-42].

A significant limitation is that these insights are derived primarily from studies of high-density, temperate urban fabrics and may not translate to low-density, hot-arid coastal resorts. Such resorts feature dispersed layouts, large open vistas, and an emphasis on scenic design, which can increase façade exposure and reduce mutual shading, leading to higher thermal loads [11, 14]. In these contexts, passive design strategies related to orientation, clustering, and aspect ratios are crucial for reducing cooling demand [43- 45]. However, current design guidance is largely derived from high-density urban case studies and lacks actionable strategies for resort-scale developments [14, 46-48]. Recent computational studies confirm solar access is sensitive to block geometry even in low-rise settings [1, 4], and the need for context-specific models in hot-arid environments is clear [3, 18].

2.2. Energy Sustainability and Renewable Integration in Resorts

Energy sustainability is a core pillar of the Sustainable Development Goals (SDGs), emphasizing the need for improved energy efficiency [49]. Urban areas dominate global energy consumption, necessitating strategies that align energy production and demand reduction with broader sustainability frameworks [15, 50]. Waterfront resorts in rapidly developing tourist zones present a unique challenge due to their high reliance on cooling and tourism-driven expansion, making them vulnerable to environmental degradation and energy inefficiency [49, 51]. Enhancing energy efficiency is therefore an operational imperative in hot-arid coastal climates [46, 47, 52].

Climate-sensitive passive design—optimizing orientation, massing, and shading—offers a powerful strategy to reduce cooling loads [53]. Importantly, reducing façade solar exposure not only minimizes cooling demand but can also improve photovoltaic (PV) system efficiency by mitigating thermal stress on panels [54, 55]. This highlights a dual benefit. However, existing research often focuses on the techno-economic feasibility of installed renewable systems [48] or general passive principles, failing to systematically quantify how upstream urban layout design (ULD) can synergistically enhance both passive savings and active renewable performance in the specific context of low-density resorts.

2.3. Microclimate, Urban Geometry, and Passive Cooling

Microclimatic performance is fundamentally influenced by urban geometry, including canyon aspect ratios and the proportion of open spaces [6, 56]. Urban form significantly affects air temperature, humidity, wind behavior, and solar radiation, particularly in high-density settings [57-59]. Orientation and courtyard configurations are effective in controlling solar gain and improving thermal comfort [60, 61], and low-energy design principles like street orientation optimization and façade shading are recognized for reducing solar radiation [62-67]. Their effectiveness is greatest when integrated early in design [7, 68].

For hot-arid coastal resorts, a critical and understudied challenge is the trade-off between shading and ventilation. Compact forms offer solar protection but often compromise wind flow, which is a critical source of thermal relief in these climates. This underscores the importance of multi-criteria simulation frameworks that evaluate urban form against competing objectives like radiation control and ventilation efficiency [2, 8]. Most existing models and studies prioritize dense urban neighborhoods, leaving a gap in tailored frameworks for low-density, tourism-driven developments where this trade-off is paramount.

2.4. Urban Layout Design (ULD) Features and Research Gaps

ULD features such as spatial patterns (linear, courtyard, wind-oriented) directly impact solar gains and natural ventilation [32, 33, 69]. Building form and spacing are also influential; compact arrangements can reduce heat loads through shading and airflow, while dispersed configurations increase solar exposure [70-73]. Orientation and urban canyon geometry further affect the thermal environment and ventilation efficiency [74, 75], as do courtyard shapes and their proportions [76, 77].

Advanced modeling approaches are essential to navigate trade-offs between minimizing heat gain and maximizing solar access for daylighting and renewables [78-83], though they can be computationally intensive [84]. There is a pressing need for more localized, climate-sensitive ULD research, where geometry is tailored to site-specific conditions to mitigate heat gain effectively [85]. These early design stages are complex, demanding strategies that address climatic responsiveness and computational feasibility [79, 86].

Synthesizing these subsections reveals a coherent research gap: While the general influence of urban form on energy use is well-established [5, 6], systematic, parametric evidence for low-density, hot-arid waterfront resorts remain scarce. Few studies explicitly test how resort-scale layout variables (open-space ratios, canyon geometry, distribution patterns) affect both passive energy savings and renewable integration potential. Moreover, most simulation frameworks prioritize dense urban neighborhoods over dispersed, tourism-driven developments. This gap is of direct relevance to global sustainability agendas as the resort sector expands in climate-vulnerable regions [49].

This study applies established parametric simulation not as a novel framework, but as a focused methodology to address this specific gap. Its contribution lies in conducting a resort-specific morphological analysis that quantifies how ULD variables influence façade-level solar radiation in low-density, view-oriented layouts, thereby translating general solar-access principles into evidence-based guidance for sustainable resort planning.

3. Methodology

3.1. Methodological Framework

This study adopts a four-stage research process (as shown in Fig. **1**) analysis, synthesis, simulation, and evaluation—adapted from Isik and Achten [87] and Cross and Roozenburg [88]. The framework enables systematic exploration of Urban Layout Design (ULD) variables for reducing solar radiation in hot-arid coastal resorts. By linking radiation reduction to cooling load savings and renewable energy system performance, the methodology bridges architectural design with energy system integration.

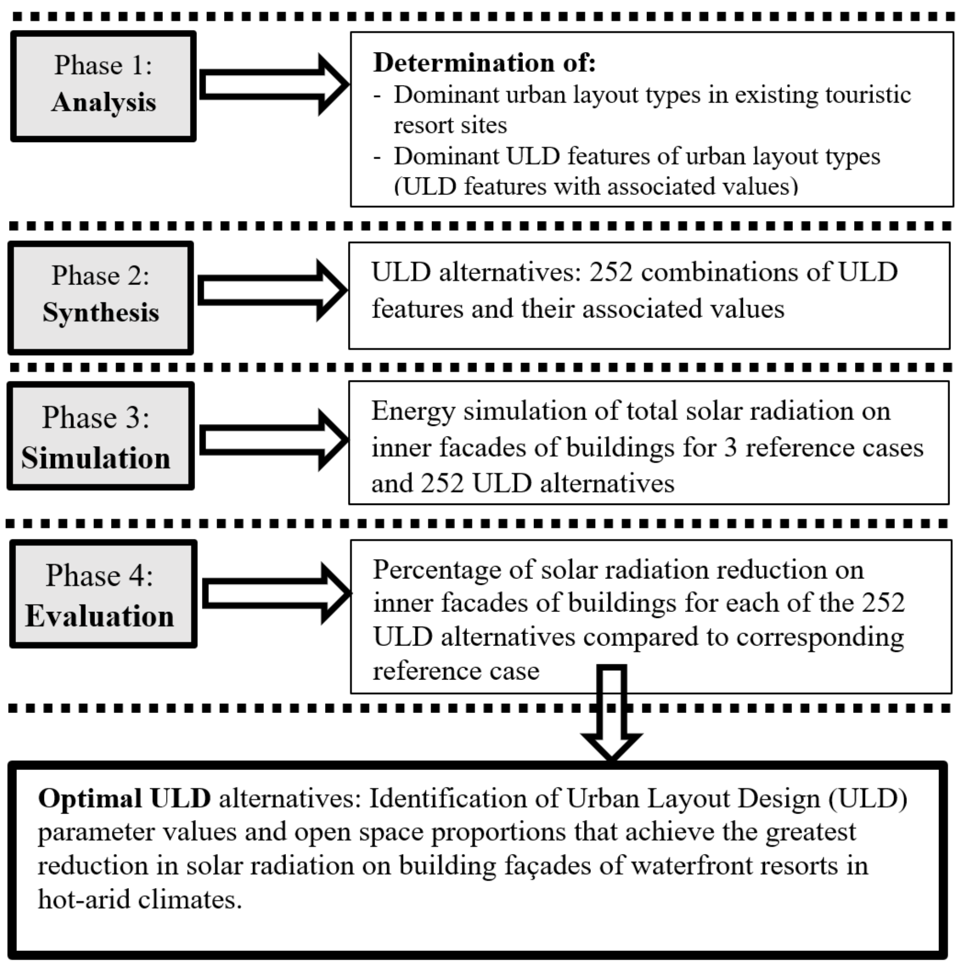


Figure 1: Methodological framework for Urban Layout Design (ULD) optimization in hot-arid coastal resorts.

3.1.1. Analysis Phase

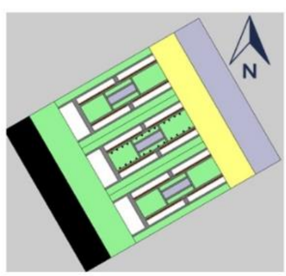
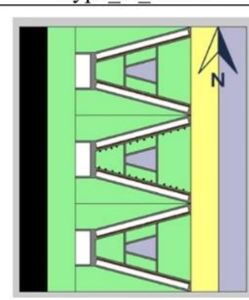
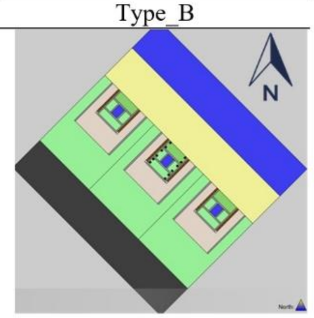
The analysis phase commenced with a field-based assessment of existing waterfront resorts along Egypt's Red Sea coast—an area known for its high energy consumption in the tourism sector and limited implementation of climate-responsive urban planning strategies [89]. This site-based investigation revealed two dominant Urban Layout Design (ULD) typologies: longitudinal linear layouts (either parallel or tilted to the shoreline) and central clustered layouts. These recurring spatial patterns provided a foundation for identifying critical ULD variables relevant to thermal performance in hot-arid coastal resorts.

From these observed configurations, four key ULD parameters were extracted and systematically categorized according to their influence on solar exposure and cooling demand:

- Open-space proportions (X:Y): These affect solar penetration levels and the depth of shading in open areas between buildings.
- Orientation: Determines the degree of exposure to direct solar radiation based on building
- Urban canyon aspect ratios (Z:X): Regulate the extent of façade shading and offer mutual protection between structures.
- Building distribution (compact vs. dispersed): Influences the degree of clustering and natural ventilation potential across the site.

These parameters were identified as primary drivers of façade-level solar loads and cooling energy requirements in waterfront resorts situated in hot-arid climates [4, 90]. Their significance lies in their ability to shape microclimatic behavior and energy efficiency at both the building and site scales. Accordingly, these features were classified based on the prevailing layout typologies observed in the Red Sea coastal zone, with their characteristics and spatial patterns summarized in Table **1**.

Table 1: Classification of ULD features and their associated values in dominant types of waterfront resort sites.

			Longitudinal linear		Central clustered
			Type_A (parallel)	Type_A_Tilted	Type_B
Urban layout types of water front resort sites **(Reference cases)**					
Features			Associated Values		
(1)	**Pattern**	shape	linear	linear	clustered
(2)	**Open-Space Shape**	Shape	longitudinal	longitudinal	central
		Space Proportion (X:Y)	1:3 , 1:4 , 1:5	1:3 , 1:4 , 1:5	1:1.2 , 1:1.5 , 1:2
(3)	**Open-Space Orientation**		E/W , NE/SW 30^{0} , 60^{0}	E/W , NE/SW 30^{0} , 60^{0}	E/W , NE/SW 15^{0} , 30^{0} , 45^{0}, 60^{0}, 75^{0}
(4)	**Urban Canyon**	Aspect Ratio (Z:X)	1:3 , 1:4 , 1:5 , 1:6	1:3 , 1:4 , 1:5 , 1:6	1:2 , 1:2.5 , 1:3
(5)	**Buildings Distribution**	Buildings Compactness	Attached , Semi-detached	Attached , Semi-detached	Attached , Semi-detached
		Buildings Orientation	Parallel	Tilted 15^{0}	Parallel

3.1.2. Synthesis Phase

To systematically evaluate design options, 252 alternative ULDs were generated by exhaustively combining the identified variables. For linear resorts, alternatives varied by three open-space ratios, four canyon ratios, three orientations, and two compactness levels, resulting in 144 scenarios. For clustered resorts, three open-space ratios, six canyon ratios, three orientations, and two compactness levels yielded 108 scenarios. This parametric approach ensured coverage of the design space while enabling sensitivity analysis of each factor.

3.1.3. Simulation Phase

The simulation phase was designed to quantify the impact of different Urban Layout Design (ULD) configurations on one primary, directly simulated variable: solar radiation exposure at the building façade level. To achieve this, all simulations were conducted using TownScope 3, a specialized tool for urban solar access analysis selected for its capability to compute direct, diffuse, and reflected radiation with hourly resolution across building surfaces [91]. The accuracy of TownScope 3 was validated by calibrating its outputs against Heliodon simulation results, confirming its reliability for this specific solar analysis across multiple urban scenarios [92].

To ensure contextual accuracy, a range of detailed input datasets was used in the simulations:

- 3D urban models were developed in AutoCAD and 3ds Max, then exported as .obj files for TownScope input.
- Climatic data specific to Hurghada—including air temperature, humidity, wind speed, and solar radiation—were sourced from Meteonorm.
- Surface material properties, such as reflectance, emissivity, and absorption, were incorporated for commonly used materials in Red Sea resorts, including plaster, interlock paving, glass, and water surfaces (Table **2**).
- Vegetation properties were also included, specifically for palm tree species like *Washingtonia* and *Phoenix dactylifera* (date palms), which are most common in Hurghada's resorts. These were modeled based on their physical dimensions and shading performance (Fig. **2**).

The direct output of this phase was the annual façade-level solar radiation value (kWh/m²) for each of the 252 design scenarios, as illustrated in Fig. (**3**). These values were benchmarked against three reference resort typologies to evaluate relative solar performance.

<u>Methodological Scope and Inferred Implications:</u>

It is critical to emphasize that this study's direct simulation output is limited to solar radiation metrics. The broader implications for cooling energy demand, outdoor thermal comfort, and photovoltaic (PV) system performance are not simulated directly but are estimated using correlations established in prior literature. This constitutes a methodological boundary.

The significance of the solar radiation reduction results is therefore interpreted through these established, secondary relationships:

- **Cooling load reduction:** Prior studies have established a correlation between lower façade solar radiation exposure and reduced cooling energy demand [1, 8]. The cooling energy savings cited in this study (e.g., 23–32%) are therefore indicative estimates derived by applying these literature-based correlations to our simulated radiation reduction values.
- **Photovoltaic (PV) integration potential:** Similarly, literature indicates that lower ambient and surface temperatures—a likely outcome of reduced solar loading—can improve PV module efficiency by mitigating thermal stress [53, 54]. Furthermore, a reduced baseline cooling demand can increase the proportional share of energy met by a given PV system. These implications for renewable energy integration are presented as inferred system-level benefits based on our primary solar data, not as direct outputs of coupled energy simulations.

This approach explicitly focuses the simulation work on generating robust, comparable solar exposure data for diverse ULDs. While the derived implications for energy and comfort are grounded in scientific literature, they represent indirect inferences. The findings on solar mitigation are presented as direct results; the associated discussions on cooling demand and PV performance are presented as logically derived, indicative outcomes to contextualize the solar data within broader sustainability goals.

Table 2: Properties of common outdoor surface materials in Hurghada (Red Sea, Egypt).

Material	Opacity (%)	Diffusion (%)	Reflection (%)	Emissivity (%)	Surface Temp. (°C)	Material
Wall (White Plaster Acrylic)	100	0	80	90	93	Wall (White Plaster Acrylic)
Roof (Concrete Tiles)	100	0	36	64	25	Roof (Concrete Tiles)
Ground (Interlock)	100	0	36	94	33	Ground (Interlock)
Windows (Glass)	12	77	7	16	60	Windows (Glass)
Vegetation (Lawns)	—	—	30	90	25	Vegetation (Lawns)
Pool (Water)	10	20	70	90	25	Pool (Water)
Road (Asphalt)	100	0	10	88	38	Road (Asphalt)
Sand	100	0	20	75	38	Sand

Date palms (Phoenix dactylifera)

Washingtonia

Figure 2: The most common palm tree types used in Hurghada Resorts.

3.1.4. Evaluation Phase

Results were evaluated through:

- Descriptive statistics (mean, range, standard deviation) to profile performance.
- Regression analysis to quantify correlations between ULD features and radiation reduction.
- ANOVA tests to assess statistical significance ($p < 0.05$).
- Performance ranking to identify optimal scenarios (>40% radiation reduction).

This analytical framework not only identifies optimal ULD configurations but also establishes quantitative links between passive design strategies, cooling load mitigation, and renewable energy efficiency — ensuring that recommendations are robust for both architectural practice and energy policy.

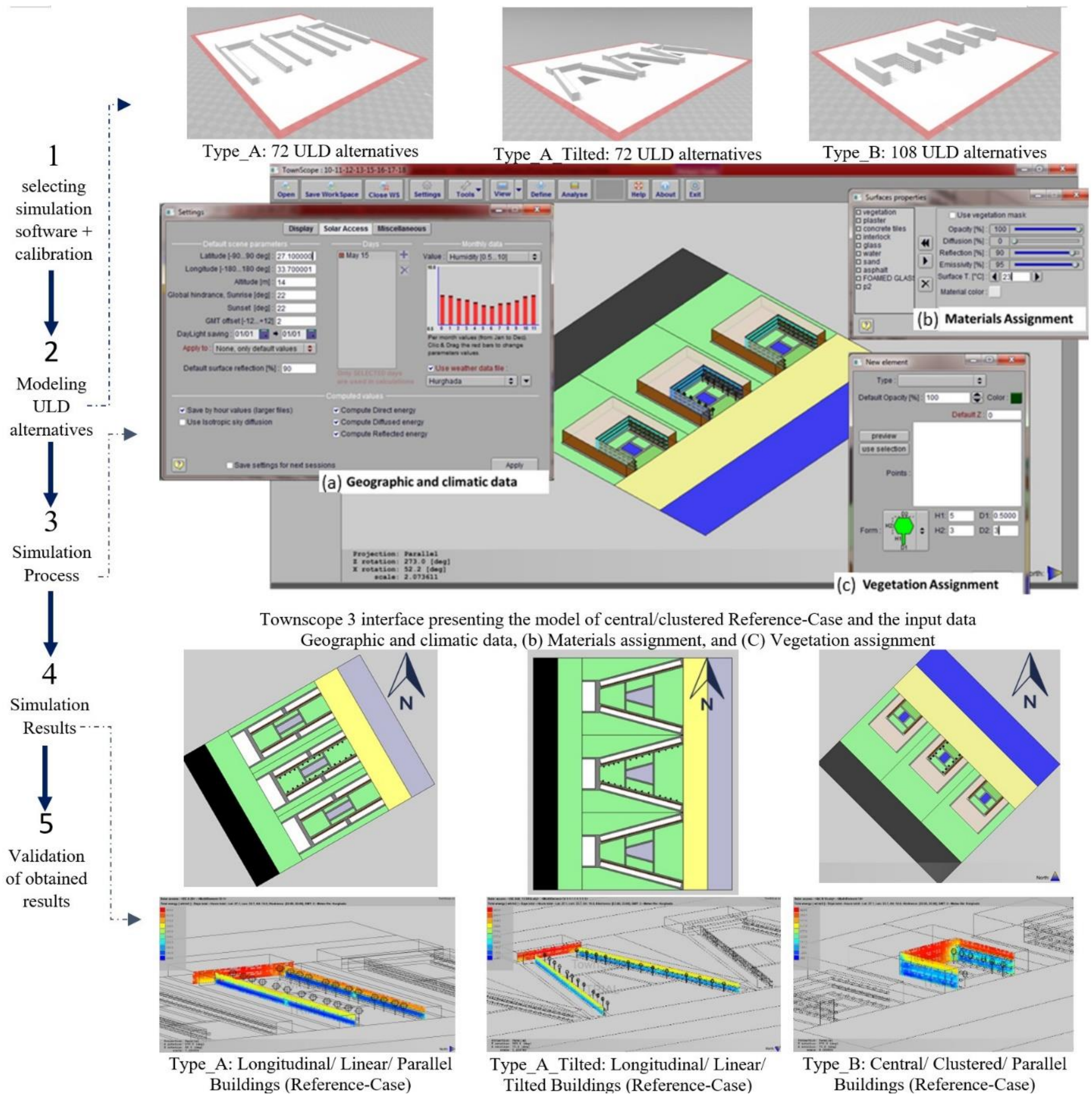


Figure 3: Sequential steps for energy simulations of the 252 generated ULD alternatives and results of solar radiation for the three reference cases of site types.

4. Results

4.1. The Influence of Urban Morphology on Façade Solar Irradiation: A Comparative Analysis

Simulation results demonstrate that urban morphology exerts a strong, statistically significant influence on façade-level solar irradiation, a primary driver of thermal load in hot-arid environments. Performance varied substantially across the three analyzed site typologies, with the Central Clustered (Parallel) layout achieving the greatest solar mitigation, followed by the Longitudinal Linear layouts.

The Central Clustered typology (Type_B) proved most effective for microclimate regulation. Compact U-shaped configurations were particularly performant. The optimal alternative (Alt_252, with X:Y = 1:2, Z:X = 1:2, East–West orientation) achieved a 46% reduction in annual façade solar irradiation. Integrating vegetation—modeled on common local palm species—provided a synergistic benefit, increasing the reduction to 48%. Within this typology, ten alternatives demonstrated high performance, with reductions between 40% and 46%, where NE/SW orientations at 15° and 30° from north were notably effective (Fig. **4**).

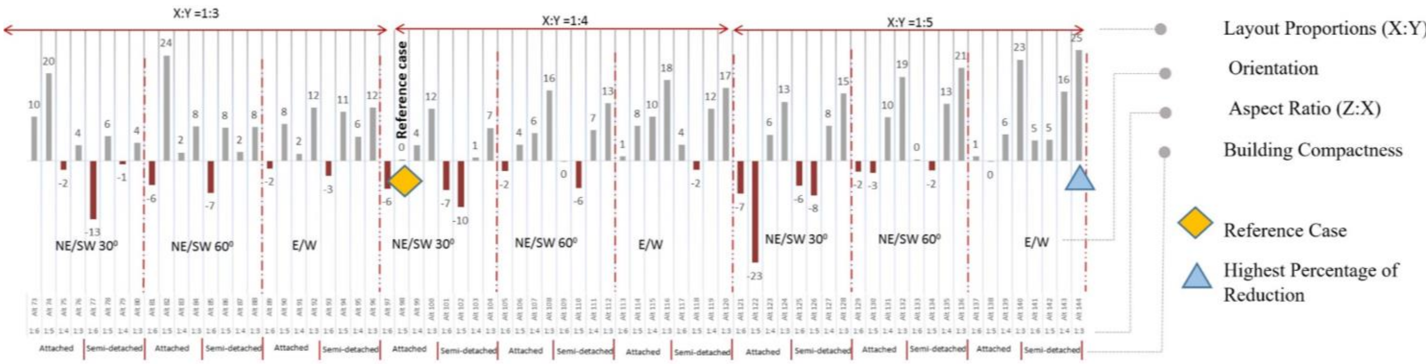


Figure 4: Percentage reduction in total solar radiation on building facades across open-spaces of waterfront resorts, comparing ULD alternatives for Type_A_Tilted (Linear-Tilted) resort site configurations.

In contrast, the Longitudinal Linear layouts showed more moderate but meaningful reductions, with performance highly dependent on orientation and canyon proportions. For the Linear-Parallel typology (Type_A), East–West orientation yielded the best outcomes, with the top-performing case (Alt_68) achieving a 29% reduction (Fig. **5**). The Linear-Tilted typology (Type_A_Tilted) demonstrated slightly lower efficacy, with its best configuration (Alt_144) reaching a 25% reduction (Fig. **6**).

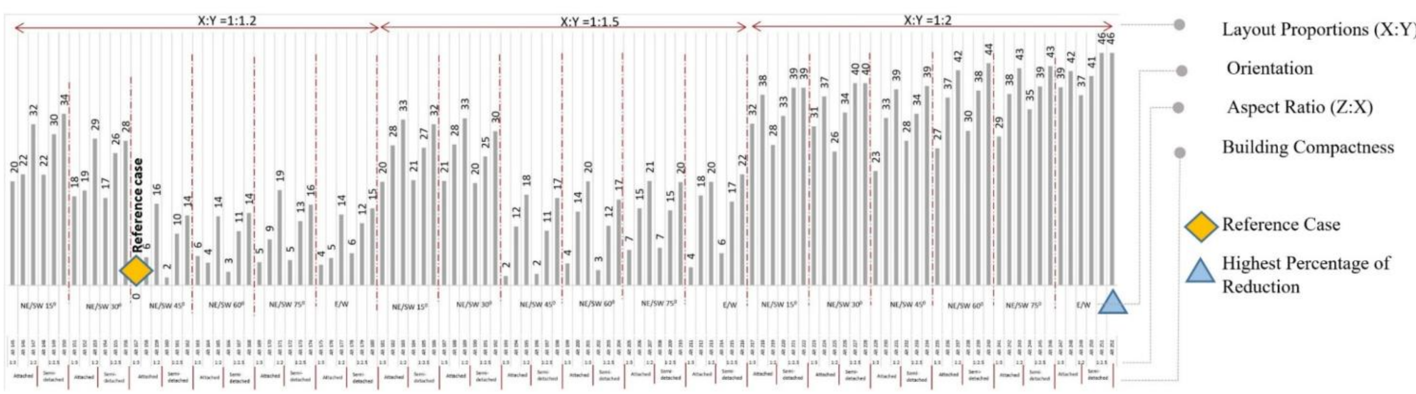


Figure 5: Percentage reduction in total solar radiation on building facades across open-spaces of waterfront resorts, comparing ULD alternatives for Type_B (Clustered-Parallel) resort site configurations.

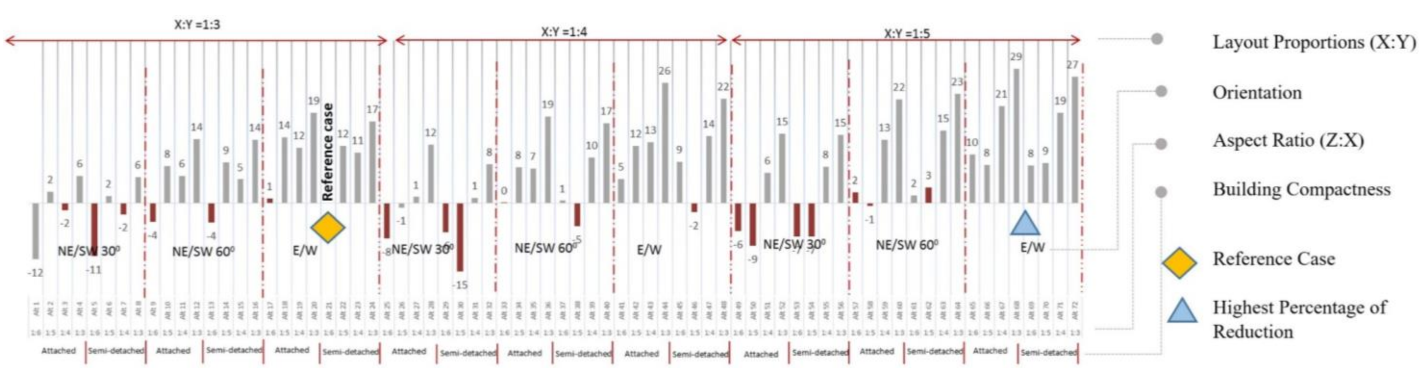
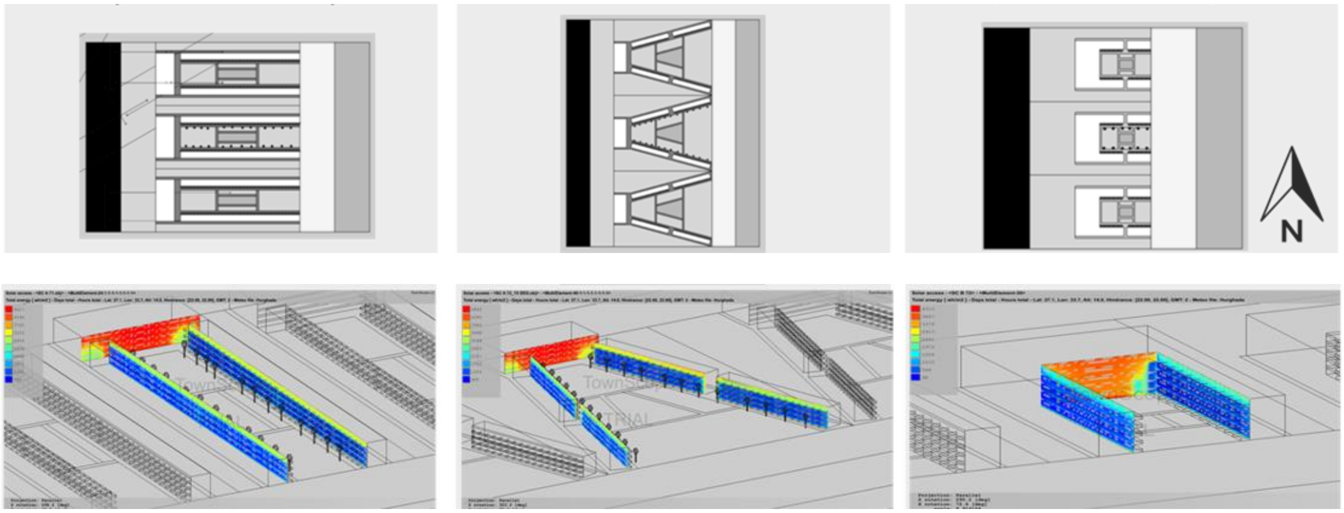


Figure 6: Percentage reduction in total solar radiation on building facades across open-spaces of waterfront resorts, comparing ULD alternatives for Type_A (Linear-Parallel) resort site configurations.

Collectively, these findings confirm that morphological variables—specifically spatial compactness, building orientation, and urban canyon aspect ratios—are critical, measurable determinants of façade-level solar irradiation. The peak reduction percentages for each typology are summarized in Fig. (**7**), and the performance ranges are synthesized in Fig. (**8**).



Type_A, percentage of reduction = 29%
Longitudinal Linear-Parallel Buildings

Type_A_Tilted, percentage of reduction = 25%
Longitudinal Linear-Tilted Buildings

Type_B, percentage of reduction = 46%
Central Clustered-Parallel Buildings

Figure 7: Maximum solar radiation reduction on building facades across open-spaces in various waterfront resort site types.

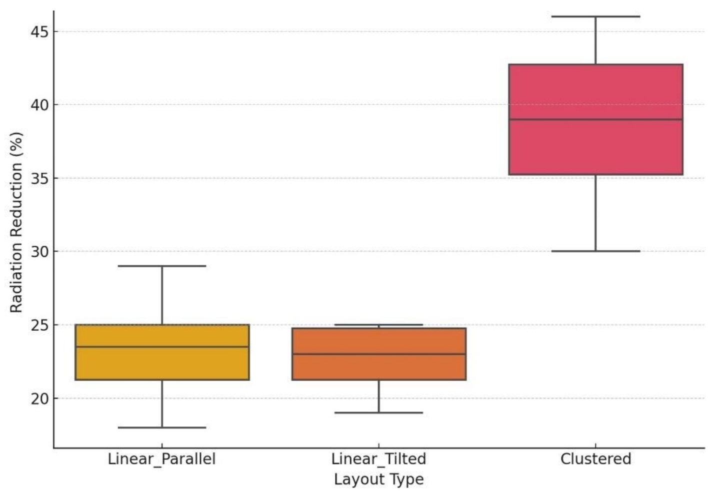


Figure 8: Ranges of solar radiation reduction on building facades across open-spaces in various waterfront resort site types.

4.2. Classification of High-Performance Morphological Alternatives for Solar Control

Analysis of the 252 scenarios reveals a clear correlation between spatial compactness and solar control efficacy. High-performing alternatives were grouped by open-space proportion (X:Y ratio):

- The most compact proportion (1:2) yielded the highest solar reductions (39–46%), dominated by compact clustered layouts.
- Moderate proportions (1:3 and 1:4) corresponded to more modest reductions (22–26%), associated with specific tilted linear and semi-compact layouts.
- The most elongated proportion (1:5) showed a wider performance range (21–29%), heavily dependent on specific alignment and canyon geometry.

This confirms that spatial compactness, combined with appropriate orientation and vertical proportions, is a primary driver for reducing radiant heat loads. To bridge simulation data with design practice, the most effective configurations within each open-space category are presented as a decision-support tool in Tables **3**, **4**, and **5**, using a color-coded visualization system.

Table 3: High-performance Urban Layout Design (ULD) alternatives for façade-level solar radiation reduction in waterfront resorts (hot-arid climate, open-space proportion X:Y = 1:2).

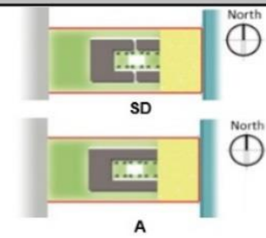
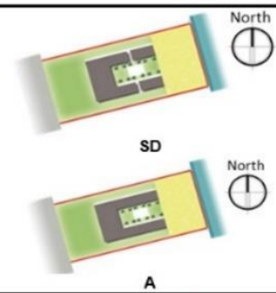
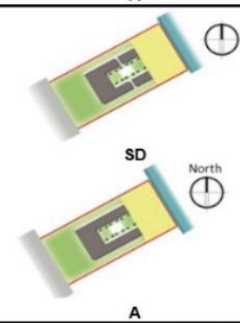
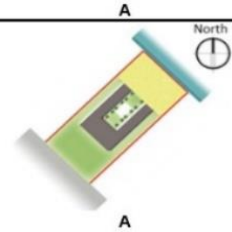
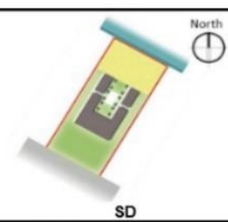
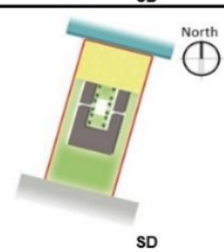
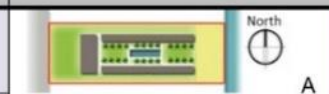
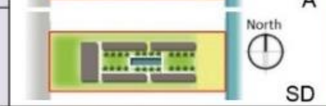
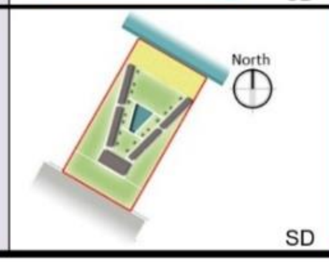
Pattern	ULD features and associated values				ULD	Percentage of reducing solar radiation
	X:Y	Orientation	Z:X	Compactness		
Clustered with U-shaped Buildings	1:2	E/W	1:2	Semi-Detached (SD)		46%
	1:2	E/W	1:2.5	Semi-Detached (SD)		46%
	1:2	E/W	1:2.5	Attached (A)		42%
	1:2	E/W	1:2	Semi-Detached (SD)		41%
Clustered with U-shaped Buildings	1:2	NE/SW 75^0	1.2	Semi-Detached (SD)		43%
	1:2	NE/SW 75^0	1.2	Attached (A)		43%
Clustered with U-shaped Buildings	1:2	NE/SW 60^0	1:2	Semi-Detached (SD)		44%
	1:2	NE/SW 60^0	1:2	Attached (A)		42%
Clustered with U-shaped Buildings	1:2	NE/SW 45^0	1:2	Attached (A)		39%
	1:2	NE/SW 45^0	1:2	Attached (A)		39%
Clustered with U-shaped Buildings	1:2	NE/SW 30^0	1:2	Semi-Detached (SD)		40%
	1:2	NE/SW 30^0	1:2	Semi-Detached (SD)		40%
Clustered with U-shaped Buildings	1:2	NE/SW 15^0	1:2	Semi-Detached (SD)		39%
	1:2	NE/SW 15^0	1:2.5	Semi-Detached (SD)		39%

Table 4: Urban Layout Design (ULD) alternatives for façade-level solar radiation reduction in waterfront resorts (hot-arid climate, open-space proportions X:Y = 1:3 and 1:4).

Pattern	ULD features and associated values				ULD	Percentage of reducing solar radiation
	X:Y	Orientation	Z:X	Compactness		
Linear with Parallel Buildings along with Space	1:4	E/W	1:3	Attached (A)		26%
	1:4	E/W	1:3	Semi-Detached (SD)		22%
Linear with Tilted Buildings by 15^0 along with Space	1:3	NE/SW 30^0	1:5	Semi-Detached (SD)		24%

4.3. Implications for Cooling Energy Demand and Outdoor Thermal Comfort

The documented reductions in solar irradiation have direct, literature-informed implications for building energy demand and outdoor space quality. Applying established correlations where a 1% reduction in solar radiation correlates with a 0.5–0.7% reduction in cooling load [1, 8], the results suggest indicative savings:

- Linear layouts (20–29% solar reduction) may achieve 10–20% cooling energy savings.
- Tilted linear layouts (up to 25% reduction) may yield 12–17% savings.
- Clustered layouts (40–48% reduction) may deliver 20–32% savings, the highest among all typologies.

Given that cooling dominates energy use in hot-arid resorts, these inferred savings signify substantial operational benefits. Furthermore, by reducing the radiant heat load on façades and adjacent spaces, these morphological strategies contribute directly to improved outdoor thermal comfort, a critical factor for resort usability.

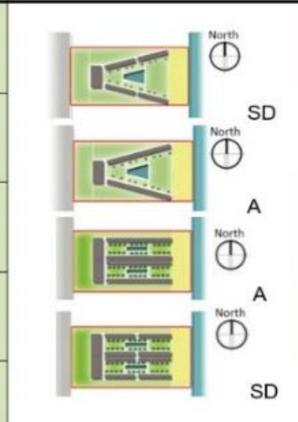
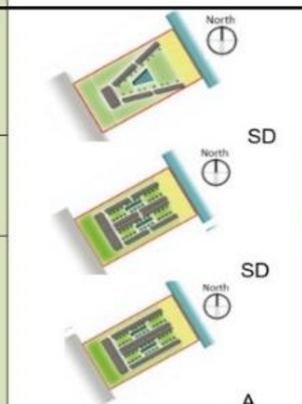
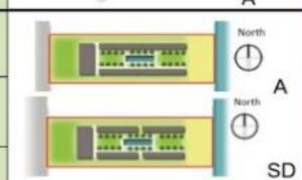
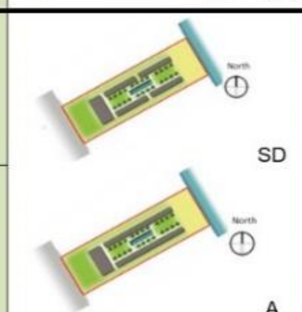
4.4. Synergies with Renewable Energy Integration and System Performance

The implications of morphological solar control extend to active energy systems. By lowering the baseline cooling demand, these passive strategies can enhance the integration efficiency of renewable energy, particularly photovoltaics (PV), based on established principles [53-55]:

- **Improved PV Performance:** Reduced surface and ambient temperatures can create more favorable operating conditions for PV modules, mitigating efficiency losses due to thermal derating.
- **Increased Renewable Energy Share:** With clustered layouts potentially reducing cooling demand by up to one-third, the proportion of total electricity demand met by a given PV installation can increase, improving economic viability.
- **Synergies with Hybrid Systems:** A lowered and flattened cooling load profile can enhance the feasibility of solar-assisted cooling and thermal storage systems.

Thus, urban morphology functions not only as a passive cooling strategy but also as a potential performance multiplier for renewable energy systems, a crucial linkage for sustainable tourism infrastructure.

Table 5: Urban Layout Design (ULD) alternatives for façade-level solar radiation reduction in waterfront resorts (hot-arid climate, open-space proportions X:Y = 1:5).

Pattern	ULD features and associated values				ULD	Percentage of reducing solar radiation
	X:Y	Orientation	Z:X	Compactness		
Linear with Tilted Buildings by 15^0 along with Space	1:5	E/W	1:3	Semi-Detached (SD)		26%
	1:5	E/W	1:3	Attached (A)		22%
Linear with Parallel Buildings along with Space	1:5	E/W	1:3	Attached (A)		29%
	1:5	E/W	1:3	Semi-Detached (SD)		27%
	1:5	E/W	1:4	Attached (A)		21%
Linear with Tilted Buildings by 15^0 along with Space	1:5	NE/SW 60^0	1:3	Semi-Detached (SD)		21%
Linear with Parallel Buildings along with Space	1:5	NE/SW 60^0	1:3	Semi-Detached (SD)		23%
	1:5	NE/SW 60^0	1:3	Attached (A)		22%
Linear with Parallel Buildings along with Space	1:5	E/W	1:3	Attached (A)		29%
	1:5	E/W	1:3	Semi-Detached (SD)		27%
	1:5	E/W	1:4	Attached (A)		21%
Linear with Parallel Buildings along with Space	1:5	NE/SW 60^0	1:3	Semi-Detached (SD)		23%
	1:5	NE/SW 60^0	1:3	Attached (A)		22%

4.5. Statistical Validation of Morphological Influence

Robust statistical analysis confirms a significant relationship between urban morphology and solar irradiation. A strong positive association exists between layout compactness and solar radiation reduction, evidenced by a Pearson correlation coefficient of 0.76. The regression slope of 7.70 and a coefficient of determination (R^2) of 0.58 indicate that as urban forms transition from linear to clustered configurations, a substantial and consistent reduction in solar exposure is achieved ($p < 0.001$).

Specifically, each incremental shift toward a more compact urban layout corresponds to an average 7.7% reduction in solar irradiation. This effect is most pronounced in canyon ratios between 1:2 and 1:3. ANOVA tests further confirm that both urban orientation and layout compactness have statistically significant individual and combined effects on radiation outcomes ($p < 0.05$). This statistical relationship is visualized in Fig. (**9**), which plots solar radiation reduction against urban layout type, annotated with key practical thresholds for design trade-offs.

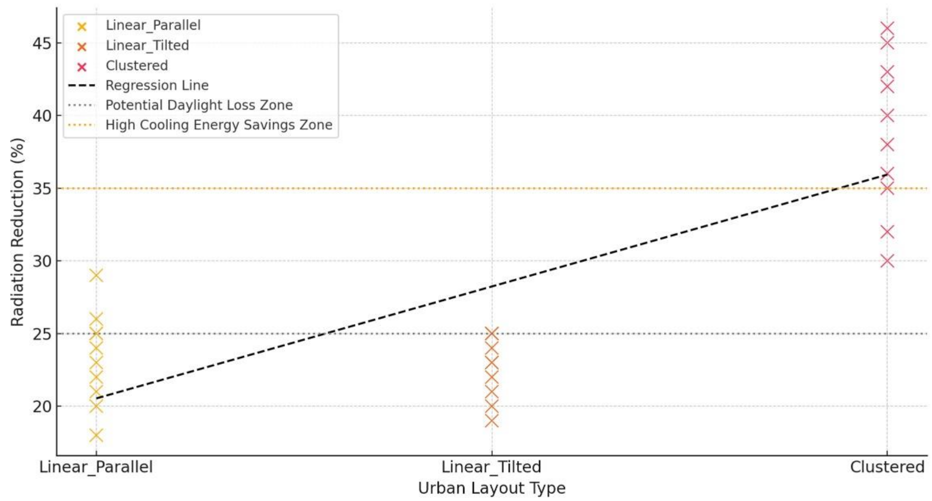


Figure 9: Regression relationship between urban layout type and solar radiation reduction, annotated with key trade-off zones.

5. Discussion

5.1. Urban Morphology as a Determinant of Microclimate and Energy Demand

This study demonstrates through direct simulation that urban morphology is a measurable and significant determinant of façade solar exposure in low-density tourism resorts. The primary finding is that clustered U-shaped configurations with integrated vegetation achieved reductions in annual façade solar irradiation of up to 48%. This simulated outcome represents a direct moderation of the urban canopy layer's radiant heat load.

The broader implications for energy demand are derived by applying correlations established in prior research. Based on literature indicating that reduced solar exposure correlates with lower cooling loads [1, 8], the achieved radiation reductions suggest potential for substantial cooling energy savings. Similarly, literature indicates that a lower ambient thermal load can improve the operating environment and effectiveness of photovoltaic (PV) systems by reducing thermal stress [54, 93]. Therefore, while this study's simulations are limited to solar radiation, the results, when contextualized with existing energy models, point toward meaningful synergies between passive urban form and active system performance. This positions context-specific urban morphology as a foundational component for climate adaptation strategies in tourism economies.

5.2. Trade-offs Between Shading, Ventilation, and Solar Access

The results highlight a fundamental design tension inherent in optimizing resort layouts. While clustered layouts maximized shading in our simulations, literature emphasizes that such compactness can compromise natural ventilation if not carefully aligned with prevailing wind patterns [32, 35]. This points to a critical trade-off in hot-arid climates between radiative cooling (via shading) and convective cooling (via airflow) that was not directly simulated in this study but is essential for holistic design.

Furthermore, the strategic addition of vegetation—which increased radiation reduction by 2% in our models—enhances evapotranspirative cooling. However, literature notes it may also inadvertently shade PV modules, potentially offsetting gains in renewable generation potential [54]. This illustrates a secondary trade-off between maximizing passive shading for microclimate regulation and preserving unshaded areas for active solar energy harvesting.

Consequently, the optimal design solution is not a single configuration but a balanced approach. Hybrid strategies cited in literature, such as selectively placed deciduous vegetation, optimized canyon aspect ratios, or adaptive shading systems, offer pathways to navigate these competing objectives [94, 95]. These strategies, combined with the performance trends identified in this study, can help designers balance scenic, climatic, and energy goals in resort master planning.

5.3. Seasonal Dynamics and Year-Round Climatic Performance

Design strategies optimized for peak summer solar mitigation may reduce valuable solar access during cooler winter months, affecting both daylight availability and potential for passive heating [96]. This seasonal dynamic is particularly relevant for year-round resort operations. Adaptive measures, including the use of deciduous vegetation, dynamic shading systems, and high-thermal-mass materials, can help mitigate these seasonal limitations and provide a more balanced performance across the annual cycle [95]. Future research should therefore extend beyond static annual performance metrics to consider dynamic, diurnal, and seasonal variations in thermal comfort and energy demand.

5.4. Integrating Solar Control and Wind Flow for Outdoor Comfort

Wind-driven ventilation remains a critical mechanism for improving outdoor thermal comfort in hot-arid resorts, and urban compactness can conflict with this if not managed carefully [16, 97]. Courtyard-type arrangements provide extensive shading but may inhibit airflow, whereas linear forms with moderate height-to-width ratios (e.g., 1.0–1.5) can offer an optimal balance by facilitating both shading and cross-ventilation [35, 97]. The early integration of solar exposure and wind flow analysis into resort master planning is crucial. This enables designers to refine these trade-offs, shaping building form, spacing, and orientation to maximize both ventilation and solar control, thereby directly enhancing the quality of outdoor spaces for guests.

5.5. Policy and Planning Implications for Climate-Responsive Resorts

The findings hold direct implications for planning authorities and resort developers in hot-arid regions:

- Tourism Planning Guidelines should integrate climate-responsive urban form criteria, ensuring that new developments adopt morphological configurations that minimize solar heat gain and moderate the local microclimate.
- Coastal Zone Management Policies could be updated to include performance-based metrics for urban canopy layer conditions, moving beyond regulations focused solely on the building envelope.
- Sustainable Tourism Certification frameworks could incentivize developers to adopt compact, climate-responsive layouts, recognizing their long-term benefits for operational energy savings and guest comfort.

By embedding these morphological principles into regulatory frameworks, governments and the tourism industry can support broader climate adaptation strategies while maintaining the economic viability of tourism-dependent coastal areas.

5.6. Global Relevance and Scalability

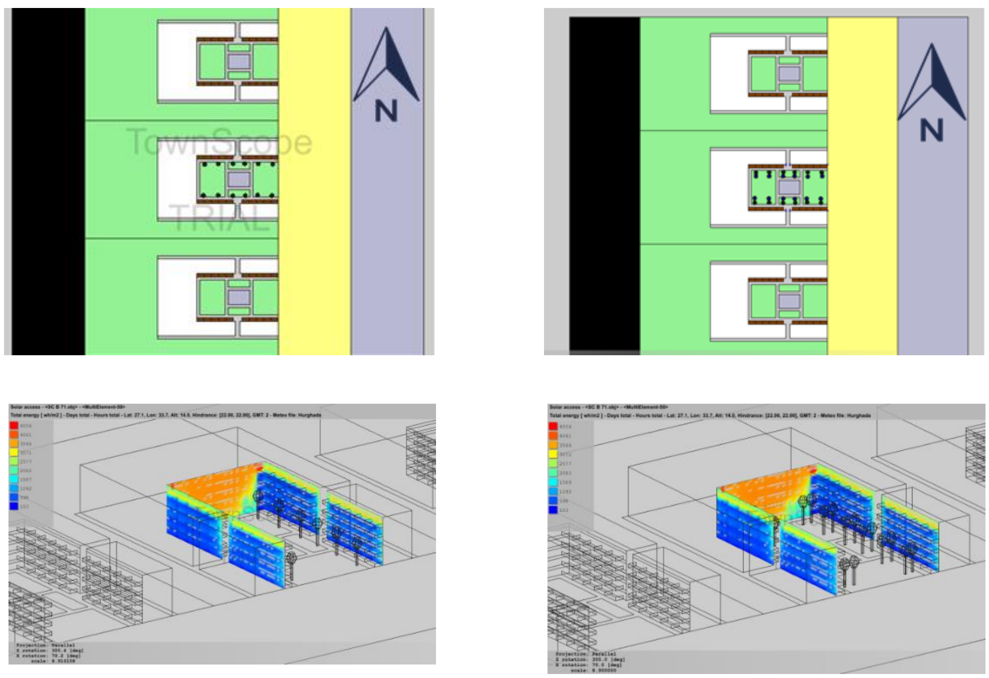
Although contextualized within Egypt's Red Sea coast, the morphological insights are transferable to coastal resorts across hot-arid and semi-arid regions globally—from the Arabian Gulf to North Africa and parts of Australia and the Americas. These regions share similar climatic stressors of intense solar radiation and are experiencing rapid tourism expansion. The results contribute to the growing discourse on sustainable tourism by demonstrating that urban form is a primary mediator between climate stress and human comfort. The findings align with global sustainability agendas [93, 98] by promoting SDG 11 through the development of sustainable human settlements and contributing to SDG 13 by implementing climate adaptation measures in vulnerable zones. The enhanced renewable energy integration facilitated by lower cooling demand further supports SDG 7.

5.7. Study Limitations and Directions for Future Research

The conclusions of this study must be considered within the boundaries of its simulation-based methodology. While the modeled scenarios captured key morphological variables, they necessarily simplify complex real-world dynamics such as transient occupant behavior, material properties, and localized wind patterns that influence microclimate and energy use.

A critical insight from this research is the nuanced trade-off between passive shading and active energy generation. For instance, the addition of a single row of palm trees in open courtyards increased solar radiation reduction from 46% to 48% (Fig. **10**), thereby enhancing passive cooling potential. However, this marginal shading gain came at the cost of reduced solar access for photovoltaic (PV) panels, slightly lowering renewable generation capacity. This exemplifies the delicate balance required in designing low-carbon resorts.

Future research should advance toward integrated performance modeling that couples urban microclimate simulations with detailed building energy models and empirical validation through on-site monitoring. Furthermore, investigations incorporating dynamic shading, hybrid renewable systems, and multi-objective optimization across different seasonal scenarios would offer deeper insights into achieving year-round energy resilience and superior outdoor thermal comfort.



Reduction of total solar radiation 46%   Reduction of total solar radiation 48%

Figure 10: Illustration demonstrates the effect of adding another row of palm trees in front of building facades, resulting in enhanced solar radiation reduction.

6. Conclusion

This study provides systematic, simulation-based evidence that urban morphology is a critical and quantifiable factor regulating façade solar exposure in low-density resorts in hot-arid coastal regions. Through the parametric analysis of 252 layout scenarios for Egypt's Red Sea coast, the research statistically validates that spatial configuration—specifically building arrangement, orientation, compactness, and vegetation integration—directly governs solar heat gain.

The key finding is that U-shaped clustered layouts with integrated vegetation achieve the highest reductions in solar irradiation (up to 48%). Statistically robust correlations confirm that increased compactness and specific canyon geometries significantly lower façade-level radiation. While the direct simulation outputs are limited to solar metrics, applying established correlations from the literature suggests these morphological strategies could lead to meaningful reductions in cooling energy demand and support improved conditions for renewable energy integration.

Therefore, the primary contribution of this work is to offer context-specific, evidence-based morphological guidance for planners and architects designing in similar climatic and developmental contexts. The findings underscore that a deliberate, solar-responsive urban form should be considered a key element in the early planning stages of coastal resorts. Future research integrating direct energy and microclimate simulation with the morphological parameters analyzed here would further strengthen the practical application of these principles for climate-resilient tourism development.

Conflict of Interest

There is no conflict of interest in financial or political aspects.

Funding

The authors acknowledge and appreciate the support of the Scholarship of Scientists for Next Generation offered to Eng. Ruwaa Bahgat by Academy of Scientific Research and Technology, Ministry of Scientific Research, Egypt.

References

[1] Singh K, Hachem-Vermette C, D'Almeida R. Solar neighborhoods: the impact of urban layout on a large-scale solar strategies application. Sci Rep. 2023; 13: 43348. https://doi.org/10.1038/s41598-023-43348-8

[2] Stracqualursi A. Climate adaptivity of urban form: an evaluation by the case study of Medina of Fès. J Build Perform Simul. 2023; 18(3-4): 351-70. https://doi.org/10.1080/19401493.2023.2251935

[3] Alfouly M, Halilovic S, Hamacher T. Evaluating urban form influence on solar exposure and corresponding building energy demands. Energy Build. 2025; 338: 115708. https://doi.org/10.1016/j.enbuild.2025.115708

[4] Fang Y, Liu Z, Jia Y, Ke M, Yang R, Cai Y, *et al*. Impact of urban block morphology on solar availability in severe cold high-density cities: a case study of residential blocks in Harbin. Land. 2025; 14(3): 581. https://doi.org/10.3390/land14030581

[5] Camporeale PE, Mercader-Moyano MP. Retrofit strategies to mitigate overheating linking urban climate modeling and urban building simulations with outdoor comfort. An urban sector in Malaga (Spain). Energy Build. 2023; 298: 113531. https://doi.org/10.1016/j.enbuild.2023.113531

[6] Liu K, Xu X, Zhang R, Kong L, Wang W, Deng W, *et al*. Impact of urban form on building energy consumption and solar energy potential: A case study of residential blocks in Jianhu, China. Energy Build. 2023; 280: 112727. https://doi.org/10.1016/j.enbuild.2022.112727

[7] Natanian J. Optimizing mixed-use district designs in hot climates: A two-phase computational workflow for energy balance and environmental performance. Sustain Cities Soc. 2023; 98: 104800. https://doi.org/10.1016/j.scs.2023.104800

[8] Rostami E, Nasrollahi N, Khodakarami J. A comprehensive study of how urban morphological parameters impact the solar potential, energy consumption and daylight autonomy in canyons and buildings. Energy Build. 2024; 305: 113904. https://doi.org/10.1016/j.enbuild.2024.113904

[9] deRoos J. Planning and programming a hotel. Ithaca (NY): Cornell University, School of Hotel Administration; 2011. Working paper.

[10] Uzezi BO. Creating a sense of spatial harmony through organic architecture (thesis). Awka: Nnamdi Azikiwe University; 2013.

[11] Yilmaz S, Mutlu E, Efe R. The effect of landscape elements on urban microclimate in coastal cities. Fresenius Environ Bull. 2020; 29(10): 8394-402.

[12] Shashua-Bar L, Hoffman ME. Vegetation as a climatic component in the design of an urban street: An empirical model for predicting the cooling effect of urban green areas with trees. Energy Build. 2000; 31(3): 221-35. https://doi.org/10.1016/S0378-7788(99)00018-3

[13] Gong FY, Zeng ZC, Zhang F, Li X, Ng E, Norford LK. Mapping sky, tree, and building view factors of street canyons in a high-density urban environment. Build Environ. 2018; 134: 155-67. https://doi.org/10.1016/j.buildenv.2018.02.042

[14] Bromberek Z. Eco-resorts: Planning and Design for the Tropics. Abingdon: Routledge; 2009.

[15] Barazesh S. Suggestions for designing sustainable touristic resort complexes: With emphasis on static cooling in hot and dry climates (dissertation). Famagusta: Eastern Mediterranean University; 2011.

[16] Shishegar N. Street design and urban microclimate: Analyzing the effects of street geometry and orientation on airflow and solar access in urban canyons. J Clean Energy Technol. 2013; 1(1): 52-6. https://doi.org/10.7763/JOCET.2013.V1.13

[17] Sanaieian H, Tenpierik M, van den Linden K, Seraj F, Shemrani SMM. Review of the impact of urban block form on thermal performance, solar access and ventilation. Renew Sustain Energy Rev. 2014; 38: 551-60. https://doi.org/10.1016/j.rser.2014.06.007

[18] Lodhi MK, Tan Y, Wang X, Suprijanto A, Imran M. Advancing urban solar assessment: A deep learning and atmospheric modelling framework for quantifying PV yield and carbon reduction. Energy Build. 2025; 338: 115717. https://doi.org/10.1016/j.enbuild.2025.115717

[19] Ben Hamouche M. Climate, cities and sustainability in the Arabian region: Compactness as a new paradigm in urban design and planning. Archnet-IJAR. 2008; 2(3): 196-208.

[20] Huang Y, Yang Y, Ren H, Ye L, Liu Q. From Urban Design to Energy Sustainability: How Urban Morphology Influences Photovoltaic System Performance. Sustainability. 2024; 16(16): 7193. https://doi.org/10.3390/su16167193

[21] Merolli J, Dervishi S. Analyzing the impact of urban morphology on solar potential for photovoltaic panels: A comparative study across various European climates. Sustain Cities Soc. 2024; 115: 105854. https://doi.org/10.1016/j.scs.2024.105854

[22] Du L, Wang H, Bian C, Chen X. Impact of block form on building energy consumption, urban microclimate and solar potential: A case study of Wuhan, China. Energy Build. 2025; 328: 115224. https://doi.org/10.1016/j.enbuild.2024.115224

[23] Chatzipoulka C, Compagnon R, Nikolopoulou M. Urban geometry and solar availability on façades and ground of real urban forms: Using London as a case study. Sol Energy. 2016; 138: 53-66. https://doi.org/10.1016/j.solener.2016.09.005

[24] Alpar S, Berger J, Mazuroski W, Belarbi R. Shape optimization of the energy efficiency of building retrofitted façade. Sol Energy. 2024; 271: 112437. https://doi.org/10.1016/j.solener.2024.112437

[25] Asfour O, Alshawaf E. Effect of housing density on energy efficiency of buildings located in hot climates. Energy Build. 2015; 91: 131-8. https://doi.org/10.1016/j.enbuild.2015.01.044

[26] Gracik S, Heidarinejad M, Liu J, Srebric J. Effect of urban neighborhoods on the performance of building cooling systems. Build Environ. 2015; 90: 15-29. https://doi.org/10.1016/j.buildenv.2015.02.037

[27] Mohajeri N, Upadhyay G, Gudmundsson A, Assouline D, Kämpf J, Scartezzini J. Effects of urban compactness on solar energy potential. Renew Energy. 2016; 93: 469-82. https://doi.org/10.1016/j.renene.2016.02.053

[28] Lima I, Scalco V, Lamberts R. Estimating the impact of urban densification on high-rise office building cooling loads in a hot and humid climate. Energy Build. 2019; 182: 30-44. https://doi.org/10.1016/j.enbuild.2018.10.023

[29] Apreda C, Reder A, Mercogliano P. Urban morphology parameterization for assessing the effects of housing blocks layouts on air temperature in the Euro-Mediterranean context. Energy Build. 2020; 223: 110171. https://doi.org/10.1016/j.enbuild.2020.110171

[30] Li J, Wang Y, Xia Y. A novel geometric parameter to evaluate the effects of block form on solar radiation towards sustainable urban design. Sustain Cities Soc. 2022; 84: 104001. https://doi.org/10.1016/j.scs.2022.104001

[31] Busato L. Passive cooling and energy efficient strategies for design of hotel on the southern coast of pernambuco (thesis). London: London Metropolitan University; 2003.

[32] Bayoumi A. Comparative wind simulation studies of different urban patterns in hot arid region: Touristic resort at Qarun Lake, Fayoum Region – Egypt. Energy Sci Technol. 2013; 5(2): 38-44.

[33] Prayitno B. An analysis on spatial permeability and fluid dynamics of wind and thermal in tropical riverside residential areas of Banjarmasin City, Indonesia. Jurnal Manusia dan Lingkungan. 2013; 20(2): 199-212.

[34] Allegrini J. Influence of morphologies on the microclimate in urban neighborhoods. J Wind Eng Ind Aerodyn. 2015; 144: 108-17. https://doi.org/10.1016/j.jweia.2015.01.013

[35] Padilla-Marcos MÁ, Feijó-Muñoz J, Meiss A. Wind velocity effects on the quality and efficiency of ventilation in the modelling of outdoor spaces. Case studies. Build Serv Eng Res Technol. 2016; 37(1): 33-50. https://doi.org/10.1177/0143624415596441

[36] Okeil A. A holistic approach to energy efficient building forms. Energy Build. 2010; 42(9): 1437-44. https://doi.org/10.1016/j.enbuild.2010.03.013

[37] El-Deeb K, El-Zafarany A, Sheriff AA. Effect of building form and urban pattern on energy consumption of residential buildings in different desert climate. In: Proceedings of the 28th International Conference on Passive and Low Energy Architecture (PLEA 2012); 2012. p. 1-6.

[38] Van Esch MME, Looman RHJ, de Bruin-Hordijk GJ. The effects of urban and building design parameters on solar access to the urban canyon and the potential for direct passive solar heating strategies. Energy Build. 2012; 47: 189-200. https://doi.org/10.1016/j.enbuild.2011.11.042

[39] Sanaieian H, Seraj F, Mohammad S, Lahijani M. Placement of semi-enclosed spaces and energy demand. In: Proceedings of the 29th International Conference on Passive and Low Energy Architecture (PLEA 2013); 2013. p. 1-6.

[40] Van NT. Optimization for passive design of large scale housing projects for energy and thermal comfort in a hot and humid climate. In: Proceedings of the 30th International Conference on Passive and Low Energy Architecture (PLEA 2014); 2014. p. 52-8.

[41] Da-long L, Hui-hui Z, Jia-ping L. Rule of long-wave radiation in enclosed building space. Energy Build. 2019; 182: 311-21. https://doi.org/10.1016/j.enbuild.2018.10.035

[42] Omran ESE, Gaber IM, Elkashef TM. Climate considerations in the planning and sustainability of Egyptian cities. In: Egypt's Strategy to Meet the Sustainable Development Goals and Agenda 2030: Researchers' Contributions. Cham: Springer; 2023. p. 207-38. https://doi.org/10.1007/978-3-031-10676-7_9

[43] Toudert FA, Mayer H. Effects of street design on outdoor thermal comfort. 2007. Available from: http://www.sci.u-szeged.hu/eghajlattan/magyar.html (accessed 13 March 2025).

[44] Hanna MS. The tourism crisis in post January 25th Egypt (thesis). Cairo: American University in Cairo; 2013.

[45] Mirzabeigi S, Razkenari M. Design optimization of urban typologies: A framework for evaluating building energy performance and outdoor thermal comfort. Sustain Cities Soc. 2022; 76: 103515. https://doi.org/10.1016/j.scs.2021.103515

[46] Štahan K. Energy-efficient architecture and sustainable urban tourism: Context, challenges and solution. In: Sustainable Tourism - Practices and Awareness. London: IntechOpen; 2018. p. 1-21. https://doi.org/10.5772/intechopen.72385

[47] Zander KK, Shalley F, Taylor A, Tan G, Dyrting S. Run air-conditioning all day: Adaptation pathways to increasing heat in the Northern Territory of Australia. Sustain Cities Soc. 2021; 74: 103194. https://doi.org/10.1016/j.scs.2021.103194

[48] Luo H, Cao S, Lu VL. The techno-economic feasibility of a coastal zero-energy hotel building supported by the hybrid wind–wave energy system. Sustain Energy Grids Netw. 2022; 30: 100650. https://doi.org/10.1016/j.segan.2022.100650

[49] Raihan A, Ibrahim S, Muhtasim DA. Dynamic impacts of economic growth, energy use, tourism, and agricultural productivity on carbon dioxide emissions in Egypt. World Dev Sustain. 2023; 2: 100059. https://doi.org/10.1016/j.wds.2023.100059

[50] Mussawar O, Mayyas A, Azar E. Built form and function as determinants of urban energy performance: An integrated agent-based modeling approach and case study. Sustain Cities Soc. 2023; 96: 104660. https://doi.org/10.1016/j.scs.2023.104660

[51] Ibrahim Z. Tourism development and the environment on the Egyptian red sea coast [Master's thesis]. Waterloo: University of Waterloo; 2009.

[52] Anthopoulos L, Kazantzi V. Urban energy efficiency assessment models from an AI and big data perspective: Tools for policy makers. Sustain Cities Soc. 2022; 76: 103492. https://doi.org/10.1016/j.scs.2021.103492

[53] Ibrahim T, Akrouch M, Hachem F, Ramadan M, Ramadan H, Khaled M, *et al*. Cooling techniques for enhanced efficiency of photovoltaic panels- Comparative analysis with environmental and economic insights. Energies. 2024; 17(3): 713. https://doi.org/10.3390/en17030713

[54] Al-Masalha I, Alsabagh A, Badran O, Alkawaldeh N, Abu-Rahmeh T, Al Alawin A, *et al*. Improving photovoltaic module efficiency using water sprinklers, air fans, and combined cooling systems. EPJ Photovolt. 2024; 15: 41. https://doi.org/10.1051/epjpv/2024037

[55] Tahir M, Dong X, Khan M, Ur Rehman I. Thermal management of solar systems: A comprehensive review of cooling methods. Sol Energy. 2025; 299: 113811. https://doi.org/10.1016/j.solener.2025.113811

[56] Zhao K, Gou Z. Influence of urban morphology on facade solar potential in mixed-use neighborhoods: Block prototypes and design benchmark. Energy Build. 2023; 297: 113446. https://doi.org/10.1016/j.enbuild.2023.113446

[57] Muhaisen A, Gadi MB. Mathematical model for calculating the shaded and sunlit areas in a circular courtyard geometry. Build Environ. 2005; 40(12): 1619-25. https://doi.org/10.1016/j.buildenv.2004.12.008

[58] Yahia MW, Johansson E. Influence of urban planning regulations on the microclimate in a hot dry climate: The example of Damascus, Syria. J Hous Built Environ. 2013; 28(1): 51-65. https://doi.org/10.1007/s10901-012-9283-8

[59] Taleghani M, Sailor D, Ban-Weiss GA. Micrometeorological simulations to predict the impacts of heat mitigation strategies on pedestrian thermal comfort in a Los Angeles neighborhood. Environ Res Lett. 2016; 11(2): 024003. https://doi.org/10.1088/1748-9326/11/2/024003

[60] Yas E, Vildan OK. Evaluation of the effects of courtyard building shapes on solar heat gains and energy efficiency according to different climatic regions. Energy Build. 2014; 73: 192-9. https://doi.org/10.1016/j.enbuild.2014.01.035

[61] Ai ZT, Mak CM. From street canyon microclimate to indoor environmental quality in naturally ventilated urban buildings: Issues and possibilities for improvement. Build Environ. 2015; 94: 489-503. https://doi.org/10.1016/j.buildenv.2015.05.030

[62] St Clair P. Low-energy design in the United Arab Emirates – Building design principles. The Environmental Design Guide. 2009:1-10.

[63] Martins TAD, Adolphe L, Krause C. Microclimate effects of urban geometry on outdoor thermal comfort in the Brazilian tropical semi-arid climate. In: Proceedings of the 28th International Conference on Passive and Low Energy Architecture (PLEA 2012); 2012. p. 1-7.

[64] El Dallal N, Visser F. A climate responsive urban design tool: A platform to improve energy efficiency in a dry hot climate. Int J Sustain Energy. 2017; 36(8): 738-53. https://doi.org/10.1080/14786451.2015.1118557

[65] Ouali K, El Harrouni K, Abidi ML, Diab Y. Analysis of open urban design as a tool for pedestrian thermal comfort enhancement in Moroccan climate. J Build Eng. 2020; 28: 101042. https://doi.org/10.1016/j.jobe.2019.101042

[66] Abd Elraouf R, Elmokadem A, Megahed N, Eleinen OA, Eltarabily S. The impact of urban geometry on outdoor thermal comfort in a hot-humid climate. Build Environ. 2022; 225: 109632. https://doi.org/10.1016/j.buildenv.2022.109632

[67] Alotaibi S, Nazari MA. District cooling in the Middle East & North Africa; history, current status, and future opportunities. J Build Eng. 2023; 77: 107522. https://doi.org/10.1016/j.jobe.2023.107522

[68] Nault E, Peronato G, Rey E, Andersen M. Review and critical analysis of early-design phase evaluation metrics for the solar potential of neighborhood designs. Build Environ. 2015; 92: 679-91. https://doi.org/10.1016/j.buildenv.2015.05.020

[69] De la Paz Pérez GA, Couret DG, Rodríguez-Algeciras JA, De la Paz Vento G. Influence of the urban context on solar protection of the vertical envelope and the cooling energy demand of buildings in Cuba. J Build Eng. 2023; 76: 107224. https://doi.org/10.1016/j.jobe.2023.107224

[70] Yang F, Qian F, Lau SSY. Urban design to lower summertime outdoor temperatures: An empirical study on high-rise housing in Shanghai. Build Environ. 2011; 46(3): 769-85. https://doi.org/10.1016/j.buildenv.2010.10.010

[71] Abed H. Effect of building form on the thermal performance of residential complexes in the Mediterranean climate of the Gaza Strip (thesis). Gaza: Islamic University of Gaza; 2012.

[72] Muhaisen A, Abed H. Effect of urban geometry and spacing on the thermal performance in the Mediterranean climate of the Gaza Strip. J Archit Plan. 2014; 26: 1-14.

[73] Sadique J, Yang XIA, Meneveau C, Mittal R. Aerodynamic properties of rough surfaces with high aspect-ratio roughness elements: Effect of aspect ratio and arrangements. Boundary-Layer Meteorol. 2017; 163(2): 203-24. https://doi.org/10.1007/s10546-016-0222-1

[74] Middel A, Häb K, Brazel AJ, Martin CA, Guhathakurta S. Impact of urban form and design on mid-afternoon microclimate in Phoenix Local Climate Zones. Landsc Urban Plan. 2014; 122: 16-28. https://doi.org/10.1016/j.landurbplan.2013.11.004

[75] Ouria M, Sevinc H. Evaluation of the potential of solar energy utilization in Famagusta, Cyprus. Sustain Cities Soc. 2018; 37: 189-202. https://doi.org/10.1016/j.scs.2017.11.011

[76] Muhaisen A, Gadi MB. Shading performance of polygonal courtyard forms. Build Environ. 2006; 41(8): 1050-9. https://doi.org/10.1016/j.buildenv.2005.04.023

[77] El-Deeb K, Sherif A, El-Zafarany A. Effect of courtyard height and proportions on energy performance of multi-storey air-conditioned desert buildings. In: Proceedings of the 30th International Conference on Passive and Low Energy Architecture (PLEA 2014); 2014. p. 1-8.

[78] Amado M, Poggi F, Amado AR. Energy efficient city: A model for urban planning. Sustain Cities Soc. 2016; 26: 476-85. https://doi.org/10.1016/j.scs.2016.06.022

[79] Das S, Day C, Hauck J, Haymaker J, Davis D. Space plan generator: Rapid generation & evaluation of floor plan design options to inform decision making. In: Proceedings of the 2016 Symposium on Simulation for Architecture and Urban Design; 2016. p. 1-8.

[80] Natanian J, Aleksandrowicz O, Auer T. A parametric approach to optimizing urban form, energy balance and environmental quality: The case of Mediterranean districts. Appl Energy. 2019; 254: 113637. https://doi.org/10.1016/j.apenergy.2019.113637

[81] Natanian J, Auer T. Beyond nearly zero energy urban design: A holistic microclimatic energy and environmental quality evaluation workflow. Sustain Cities Soc. 2020; 56: 102094. https://doi.org/10.1016/j.scs.2020.102094

[82] MeshkinKiya M, Paolini R. Uncertainty of solar radiation in urban canyons propagates to indoor thermo-visual comfort. Sol Energy. 2021; 221: 545-58. https://doi.org/10.1016/j.solener.2021.04.033

[83] Wang W, Liu K, Zhang M, Shen Y, Jing R, Xu X, *et al*. From simulation to data-driven approach: A framework of integrating urban morphology to low-energy urban design. Renew Energy. 2021; 179: 2016-35. https://doi.org/10.1016/j.renene.2021.08.036

[84] Bernal M, Haymaker JR, Eastman C. On the role of computational support for designers in action. Des Stud. 2015; 41: 163-82. https://doi.org/10.1016/j.destud.2015.08.001

[85] Lin P, Gou Z, Lau SSY, Qin H. The impact of urban design descriptors on outdoor thermal environment: A literature review. Energies. 2017; 10(12): 2151. https://doi.org/10.3390/en10122151

[86] Rezaee R, Brown J, Augenbroe G, Haymaker J. The application of inverse approach to the early stage of performance-based building design. In: Proceedings of the 14th Conference of International Building Performance Simulation Association; 2015. p. 1801-8.

[87] Isik E, Achten G. Can we use digital twin technology in the design process? A theoretical framework. In: ArchDesign '22: Proceedings of the 9th International Conference on Architecture and Design; 2022. p. 45-52.

[88] Cross N, Roozenburg N. Modeling the design process in engineering and in architecture. J Eng Des. 1992; 3(4): 325-37. https://doi.org/10.1080/09544829208914765

[89] Central Agency for Public Mobilization and Statistics (CAPMAS). Statistical Yearbook. Egypt: CAPMAS; 2016.

[90] Bahgat R, Reffat RM, Elkady SL. Analyzing the impact of design configurations of urban features on reducing solar radiation. J Build Eng. 2020; 32: 101664. https://doi.org/10.1016/j.jobe.2020.101664

[91] Azar S. TownScope 3 software: Description. 2018. Available from: http://www.townscope.com/index.php (accessed 13 March 2025).

[92] Heliodon. 2024. Available from: http://heliodon.net/heliodon/index.html (accessed 13 March 2025).

[93] United Nations Human Settlements Programme (UN-Habitat). World Cities Report 2020: The Value of Sustainable Urbanization. 2021. Available from: https://unhabitat.org/world-cities-report (accessed 13 March 2025).

[94] Mahmoud AH. Analysis of thermal comfort conditions in an outdoor urban setting: The case of Cairo, Egypt. Build Environ. 2011; 46(5): 605-15. https://doi.org/10.1016/j.buildenv.2010.09.009

[95] Kim Y, Kim Y. Energy and daylighting analysis of automated dynamic shading systems in buildings. Build Environ. 2020; 169: 106543. https://doi.org/10.1016/j.buildenv.2019.106543

[96] Haggag M, Hassan A. Experimental study on the performance of passive cooling techniques in residential buildings at arid climate. Renew Energy. 2015; 83: 232-44. https://doi.org/10.1016/j.renene.2015.04.044

[97] Mahmoud SH, Gan TY. Long-term impact of rapid urbanization on urban climate and human thermal comfort in hot-arid environment. Build Environ. 2018; 142: 83-100. https://doi.org/10.1016/j.buildenv.2018.06.022

[98] Kim J, Park C, Lee J. Integration of PV systems on vertical facades: Performance analysis in hot and arid environments. Renew Energy. 2022; 187: 185-98. https://doi.org/10.1016/j.renene.2022.01.017