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Review

Urban Microclimate and Energy Modeling: A Review of Integration Approaches

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Abstract: Current building energy modeling (BEM) tools lack the capability to inherently simulate the impacts of urban microclimates on building energy performance. While efforts have been made to integrate BEM with Urban Microclimate Modeling (UMM) tools, their ability to capture spatial and seasonal microclimate variations remains limited. This review critically evaluates existing urban microclimate-integrated BEM approaches and their effectiveness in modeling the complex interactions between urban form, microclimate, and building energy performance. Through an analysis of 94 research articles, the review first examines the influence of urban form on microclimates, followed by an assessment of how microclimatic conditions impact building energy use. Additionally, it evaluates conventional modeling frameworks employed in BEM tools and their limitations in representing dynamic microclimatic variations. The findings emphasize the non-linear heat exchange relationships between urban form and microclimate, typically modeled using computationally intensive Computational Fluid Dynamics (CFD)-based UMM tools. This review introduces a classification of heat exchange types: atmospheric heat exchange, involving air temperature, wind, and humidity, and non-atmospheric heat exchange, driven by radiative interactions with surrounding urban surfaces. The study further highlights that modifying standard weather files and heat transfer coefficients alone is insufficient for BEM tools to accurately capture near-surface microclimate variations. By identifying critical insights and research gaps, this review establishes a foundation for advancing next-generation urban microclimate-integrated BEM approaches, emphasizing the need for computationally efficient and dynamically responsive modeling techniques.

Keywords: building energy modeling; coupling; chaining; heat transfer; microclimate; urban form

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1. Introduction

Currently, 56% of the world's population resides in urban areas, accounting for 78% of global energy consumption [1]. By 2050, this proportion is expected to rise to 68%, further increasing global energy demand [2]. Urbanization trends, combined with climate change effects such as urban heat islands (UHIs), exacerbate energy consumption in cities [3–5]. The densification of built environments reduces vegetation cover, raises surface temperatures, and increases reliance on mechanical cooling. Additionally, intensified human activities and infrastructure expansion contribute to rising baseline energy demand, further straining urban energy systems. Beyond energy impacts, UHIs pose serious health risks, particularly heat-related illnesses in densely populated urban areas.

To enhance energy efficiency in urban buildings, architects and urban planners increasingly employ building energy modeling (BEM) tools. These tools analyze key parameters

such as geometry, materials, occupant behavior, and equipment use to simulate energy consumption accurately. They also support the identification and implementation of energy-saving strategies [6,7]. Recent advancements in BEM tools include co-simulation features that enable dynamic energy-saving strategy evaluations [8,9]. Emerging solutions, such as thermochromic coatings and nature-based strategies (e.g., green facades, urban vegetation), contribute to energy savings by mitigating heat buildup and improving local microclimates [10–12]. However, their effectiveness depends significantly on strategic placement and seasonality, which conventional BEM tools struggle to quantify accurately.

1.1. Limitations of Simulating Urban Microclimate Impacts

Present-day BEM tools are not inherently designed to simulate the effects of urban microclimates on building energy performance [13,14]. Traditionally, they rely on weather datasets derived from Typical Meteorological Year (TMY) or Test Reference Year (TRY) files [15], often sourced from suburban or rural locations. Consequently, these tools fail to account for urban-specific microclimatic conditions such as UHIs, localized wind patterns, and radiation effects. These omissions lead to energy performance errors of up to 200%, affecting both building energy consumption predictions and the assessment of microclimate-responsive strategies [16].

To address these inaccuracies, researchers have integrated BEM with Urban Microclimate Modeling (UMM) tools. Critical reviews by Lauzet et al. [16], Rodler et al. [17], and Sezer et al. [18] have mapped existing methodologies for BEM-UMM integration. However, a detailed evaluation of how well these approaches capture the diverse microclimatic influences of urban elements remains absent. Specifically, the inbuilt mechanisms within BEM tools that attempt to model spatial and seasonal variations of urban microclimates have not been systematically analyzed.

1.2. Overall Aim of This Review

This review assesses the current scope of urban microclimate-integrated BEM approaches in simulating the effects of microclimates on building energy performance. It has the following specific aims:

1. Examine the influence of urban form on microclimates, considering parameters such as density, vegetation, and material properties.
2. Analyze how urban microclimates impact building energy performance, with a focus on atmospheric and non-atmospheric heat exchanges.
3. Evaluate the strengths and limitations of current BEM-UMM integration approaches, identifying computational challenges and accuracy concerns.

By synthesizing existing knowledge and highlighting gaps, this review establishes a foundation for improving urban energy modeling and informing climate-responsive building design.

2. Methodology of the Review

This review adopts a three-stage methodology to systematically search, filter, and analyze peer-reviewed literature, focusing on (Figure 1) the following:

1. The impacts of urban form on microclimate;
2. The influence of urban form and microclimate on building energy performance, including inbuilt mechanisms within BEM tools;
3. The advantages and limitations of state-of-the-art urban microclimate-integrated BEM approaches.

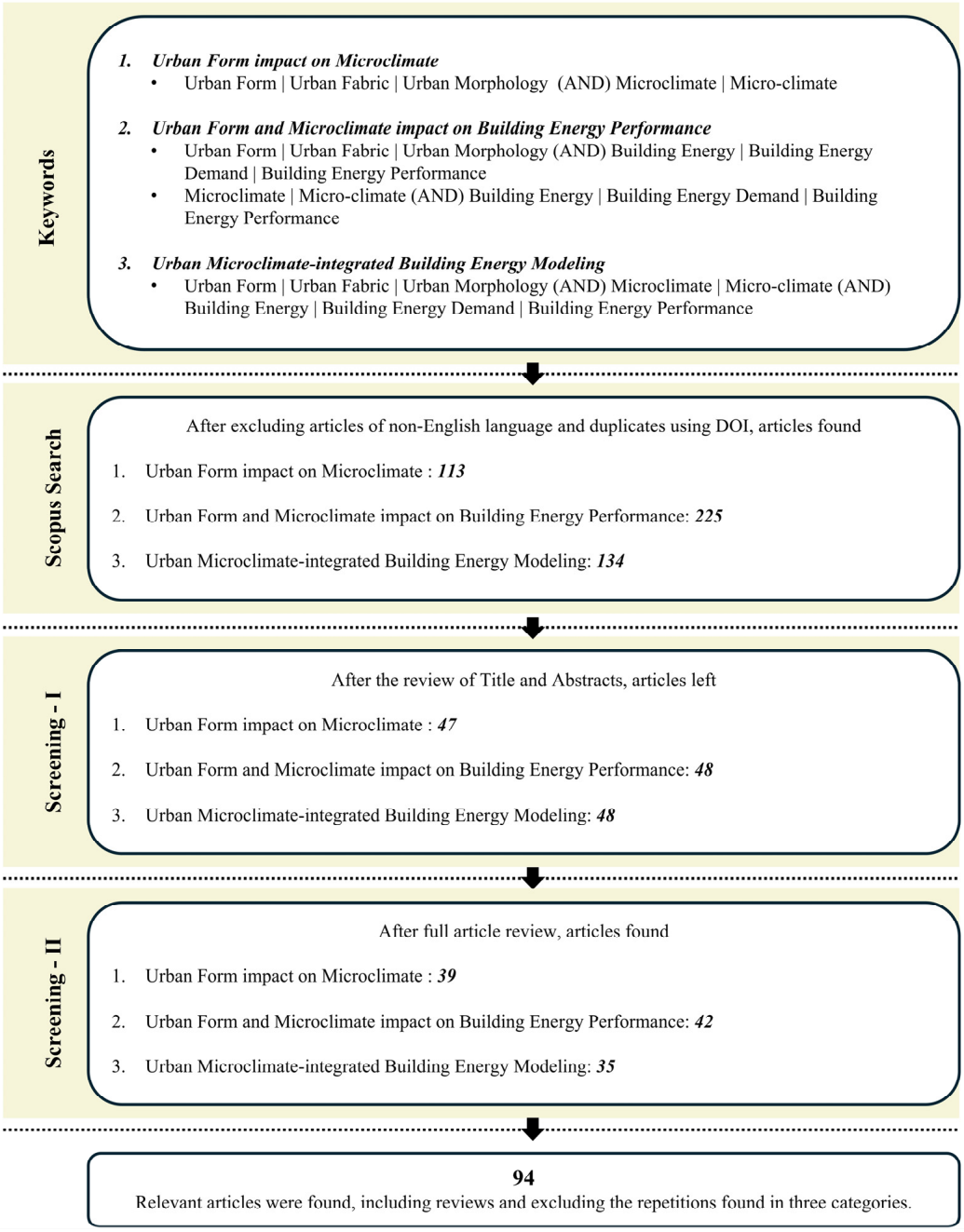


Figure 1. The three-stage literature search and screening process.

The initial literature search was conducted using open-access platforms such as Google Scholar and ResearchGate to identify commonly used keywords. These keywords were then applied to the Scopus database using logical operator combinations (e.g., "Urban Form" AND "Microclimate"), generated via Python 3.11 and supplied to the Scopus API [19].

Duplicate entries were filtered based on their digital object identifier (DOI). This review also employed the PRISMA-based systematic screening procedure [20,21]. The screening process included the following:

- Screening I: Reviewing titles and abstracts to identify relevant studies.
- Screening II: Conducting an in-depth analysis of selected articles, focusing on methodologies used to model heat exchanges between buildings and urban microclimates. Studies providing insights across multiple review stages were prioritized.

Since this review focuses on urban microclimate-integrated BEM approaches, studies that specifically interlink urban building energy modeling (UBEM) with UMM tools were excluded. This decision was based on concerns regarding the conventional approach of selecting intermediary floors in physics-based UBEM tools and the reliance of reduced-order and data-driven UBEM models on standard weather datasets, which may not adequately capture spatio-seasonal variations [22]. Furthermore, to avoid redundancy, only studies that propose distinct integration methodologies were included.

The structure of the review follows this organization:

- Section 3 evaluates the impacts of urban form on microclimate, emphasizing non-linear interactions and the UMM tools used for their simulation.
- Section 4 examines the influence of urban form and microclimate on building energy performance, along with BEM tool capabilities and challenges.
- Section 5 reviews existing integrated modeling approaches, assessing their effectiveness and limitations.
- Section 6 synthesizes key insights and highlights gaps that must be addressed for advancing urban microclimate-integrated BEM approaches.

3. Impacts of Urban Form on Microclimate

Urban form consists of the morphological and material characteristics of buildings, vegetation, pavements, roads, and water bodies, all of which influence local microclimates. These elements affect heat gains, losses, and wind patterns, leading to complex interactions that shape urban thermal and airflow conditions.

Studies analyzing these impacts typically use two- and three-dimensional (2D and 3D) urban form metrics (see Table 1). Contrary to conventional assumptions, the influence of urban elements on microclimate is highly non-linear and context-dependent. The following subsections discuss key findings from previous research, focusing on how buildings, greenery, pavements, and water bodies contribute to microclimatic variations. Additionally, this section introduces UMM tools capable of simulating these interactions.

Table 1. Definition of design metrics.

Design Metric	Definition
3D Shape Index	Ratio of a building's surface area to the minimum surface area of the most compact sphere.
Building Density	Proportion of the total site area occupied by buildings.
Building Surface Coverage	Ratio of a building's outer surface area to the ground area it covers.
Construction View Index	Percentage of an image occupied by structures above ground level.
Dimension of 3D Fractal	Density and closeness of buildings within an urban area.
Drag Coefficient	Reduction in energy within a moving fluid due to the shape and structure of encountered objects.
Floor-to-Area Ratio	Ratio of a building's total floor area to the land size upon which it is built.
Green Coverage Rate	Fraction of an area occupied by green spaces.
Green Plot Ratio	Ratio comparing the total area covered by greenery to the overall site area.
Green View Index	Percentage of an image occupied by green spaces or vegetation.
Impervious Ground Surface	Ratio of impervious surfaces to the entire site area.
Road and Pavement View Index	Percentage of an image covered by roads and pavements.
Shape Coefficient	Ratio of a building's external surface area to its internal volume.
Sinuous Configuration	Regular pattern of building placement along the *XY*-axis.
Sky View Factor	Degree of openness or exposure of a surface to the sky.
Street Entry-Type Streets	Ratios of height to width and their orientations along street interfaces.
Surface Area Ratio	Fraction of a building's exterior surface exposed to open air.
Weighted Average Height	Central tendency of building heights within an area, considering the significance of each building's height.

3.1. Effects of Buildings on Microclimate

Building morphology—including height, density, orientation, and surface materials—significantly influences urban microclimates. These factors regulate solar radiation absorption, wind patterns, and heat retention, resulting in temperature variations within the urban environment. Buildings with low-albedo surfaces absorb and re-emit more heat, contributing to increased ambient air temperatures and intensifying urban heat islands (UHIs) [23,24]. In contrast, high-albedo materials reflect solar radiation, mitigating localized warming [25,26]. Reflected radiation from surrounding structures can also amplify heat absorption by adjacent buildings, further increasing the heat load (Figure 2).

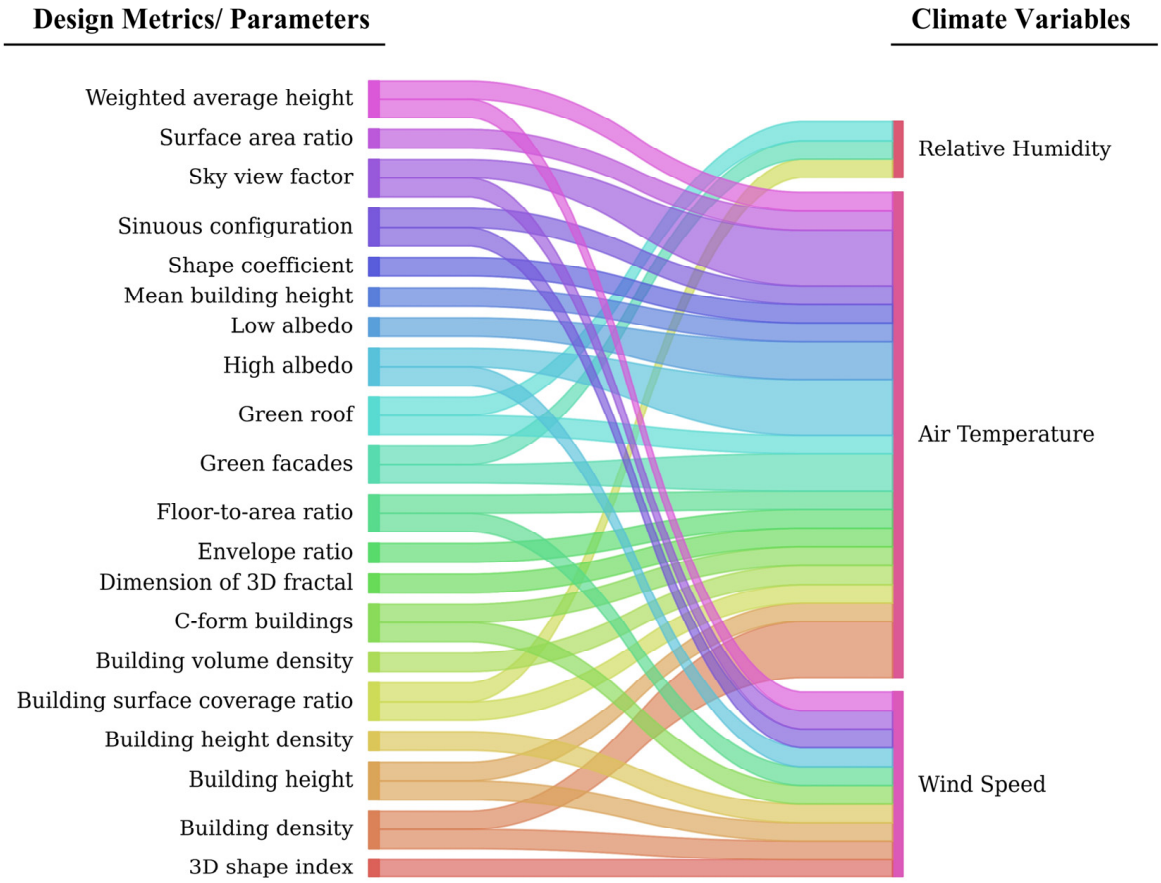


Figure 2. Building morphological and material parameters influencing Air Temperature [23–39], Relative Humidity [27–29] and Wind Speed [27,32–35].

To mitigate these effects, green roofs and green walls have been widely implemented, reducing heat gains through shading and promoting cooling via evapotranspiration [26,28,39]. This process enhances localized cooling by releasing moisture into the atmosphere, which is particularly effective in arid climates where ambient humidity is low [40]. Additionally, green surfaces reduce exposure to re-radiated heat from surrounding structures, further lowering heat absorption [12,41]. While vegetation helps moderate urban temperatures, it can also increase atmospheric moisture content, potentially raising relative humidity levels [12].

Wind dynamics also play a crucial role in shaping urban microclimates. Higher wind speeds facilitate heat dissipation and enhance convective cooling, explaining the observed negative correlation between surface area ratio and air temperature [42]. Furthermore, increased wind speeds enhance mixing between air layers, accelerating evaporative cooling and reducing relative humidity in urban areas [43,44]. However, densely built

environments can obstruct airflow, leading to localized heat retention. Wind dynamics are highly dependent on urban morphology, wind direction, and pressure differences, further emphasizing the complex interactions between building materiality, form, and microclimatic regulation.

3.2. Effects of Greenery and Water Bodies on Microclimate

Urban greenery and water bodies play a crucial role in regulating microclimates by influencing air temperature, humidity, and wind behavior (Figure 3). Vegetation reduces air temperature through shading and evapotranspiration, with studies showing that urban green spaces significantly lower local temperatures [31,32,36]. However, the magnitude of cooling varies based on vegetation type and spatial configuration. For example, trees provide more effective cooling than lawns due to their higher shading capacity [37], yet the cooling effect of greenery diminishes beyond a certain spatial threshold, as observed in studies near waterfront blocks, where temperature reductions plateaued with increasing green space width [45].

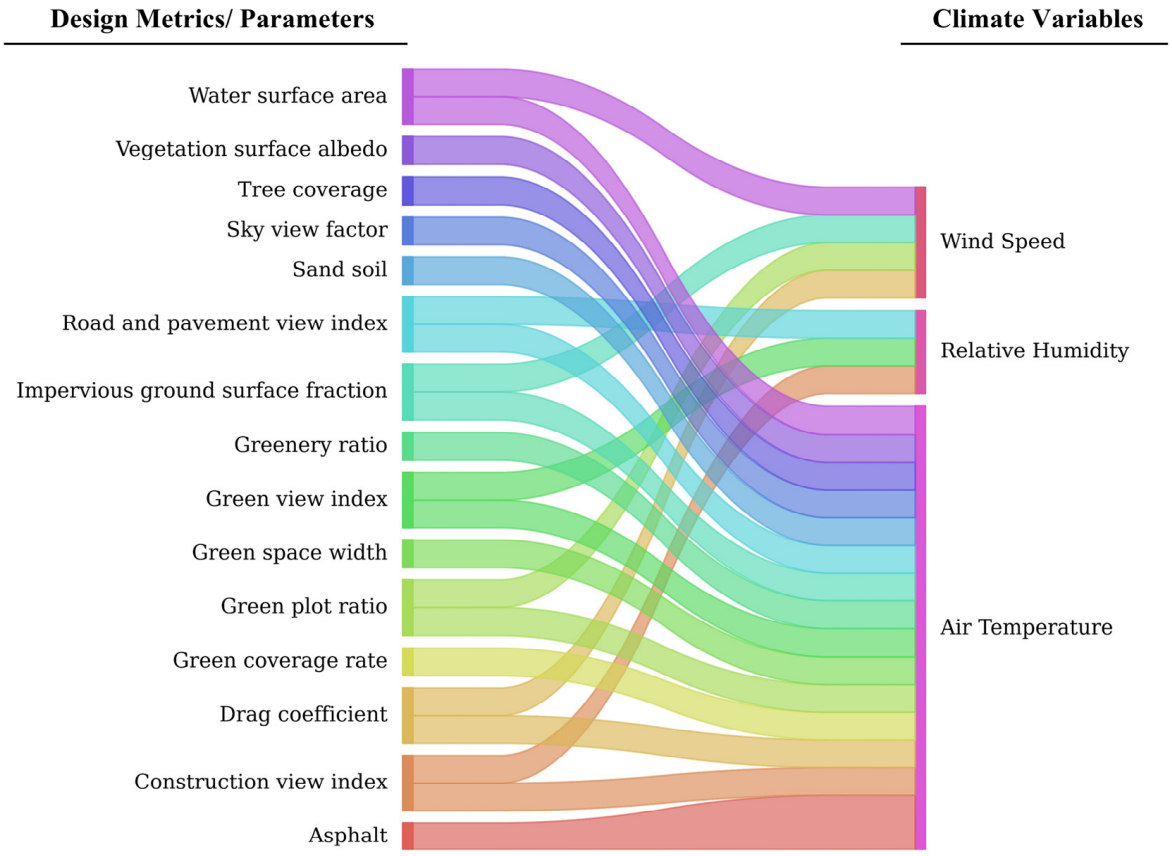


Figure 3. Design metrics/parameters of greenery and vegetation, pavements and roads, and water body-related influences on climate variables [31,32,37,38,42,45–48].

Similarly, water bodies exhibit complex thermal behavior, cooling the air during the day through evaporation while retaining heat at night, sometimes leading to localized warming. The effectiveness of water-based cooling is highly climate-dependent, being more pronounced in arid environments where evaporation rates are higher but less effective in humid regions due to already elevated moisture levels [47]. Additionally, the microclimatic influence of greenery and water bodies is significantly affected by wind patterns, which can either enhance cooling effects by promoting convective airflow or, in dense urban settings, trap moisture and lead to higher humidity levels. These findings underscore the

context-dependent nature of greenery and water bodies in shaping urban microclimates, emphasizing the need for strategic placement and integration with urban design elements.

3.3. Effects of Pavements and Roads on Microclimate

Paved surfaces, such as asphalt roads and concrete sidewalks, significantly contribute to urban heat buildup due to their low reflectivity and high thermal mass. Low-albedo pavements absorb and retain heat, raising local temperatures with increase in coverage [46]. In contrast, high-albedo materials can reduce air temperatures by reflecting more solar radiation, though their effectiveness depends on direct solar exposure and material composition [49].

Additionally, some green pavement materials retain moisture and later release it through evaporation, increasing local humidity levels [31]. However, this effect is highly dependent on climatic conditions—while evaporative cooling is beneficial in dry environments, it becomes less effective in humid settings. Roads and pavements also alter wind behavior, affecting near-surface airflow patterns and thermal exchanges.

These interactions underscore the non-linear influence of urban materials on microclimatic conditions, demonstrating how surface properties, spatial arrangement, and environmental factors collectively shape urban climates.

3.4. Urban Microclimate Modeling

A significant proportion of studies (68%) examining urban microclimate effects rely on Urban Microclimate Modeling (UMM) tools, which are broadly categorized into Computational Fluid Dynamics (CFD) models and energy balance (EB) models [50]. CFD models, such as ENVI-Met, OpenFOAM, and ANSYS Fluent, simulate airflow, heat transfer, and pollutant dispersion at high spatial resolution. These models effectively capture wind–vegetation interactions and spatial temperature variations but require significant computational resources, limiting their feasibility for large-scale or long-term simulations. In contrast, EB models, including Town Energy Balance (TEB) and Canopy Air Temperature (CAT) [51,52], focus on thermal exchanges and surface energy balance calculations. While they provide faster simulations suited for larger urban areas, they lack the detailed representation of wind dynamics available in CFD models. For high-resolution, seasonally varying urban microclimate assessments, CFD-based UMM tools are generally preferred over EB models, despite their computational demands [53].

4. Impacts of Urban Form and Microclimate

The influence of urban microclimate on building energy performance is determined by both urban form and local climatic conditions. Buildings exchange heat with their surrounding microclimate primarily through convective, ventilation-driven, and radiative heat transfer mechanisms [54]. Convective heat transfer occurs between air and building surfaces and is influenced by factors such as air temperature, surface temperature, and wind speed and direction. Interestingly, convective heat transfer is more effective at lower wind speeds, as higher wind velocities reduce the formation of thermal boundary layers [55].

Ventilation-driven heat exchange, on the other hand, occurs when outdoor air replaces indoor air and is affected by wind speed, pressure differentials, and building openings [56]. This process includes air infiltration and exfiltration through cracks and openings, commonly referred to as discharge heat transfer. The effectiveness of discharge heat transfer depends on building geometry, the size and placement of openings, and external wind conditions. Since both convective and discharge heat transfers are driven by air movement, they are collectively categorized as atmospheric heat exchange in this study.

Beyond convection, buildings also gain and lose heat through radiative heat exchange [57,58]. Shortwave radiation interactions between buildings and adjacent surfaces

create multiple inter-reflections, amplifying radiative heat exchanges and affecting heating and cooling demands [59]. A building's ability to emit or reflect radiation depends on its thermal and optical properties, material composition, and surrounding wind conditions [58,60]. Unlike atmospheric heat exchange, radiative heat transfer does not require air as a medium, which is why it is referred to as non-atmospheric heat exchange in this study.

Urban morphology and material composition vary widely, leading to differential heating of surfaces, wind speed variations, and temperature fluctuations [61,62]. These factors significantly influence both atmospheric and non-atmospheric heat exchanges, emphasizing the need for a detailed examination of how contemporary BEM tools model these effects. The following subsections discuss the methodologies used in BEM tools to simulate convective, discharge, and radiative heat transfers.

4.1. Convective Heat Exchange Modeling

Convective heat exchange between a building's surface and the surrounding environment is determined by surface conductance, surface area, temperature differentials, and the convective heat transfer coefficient (CHTC). Most present-day BEM tools rely on typical or test reference weather files, which provide identical or extrapolated hourly air temperature and wind speed data for all building surfaces. For instance, EnergyPlus extrapolates wind speed data from meteorological records based on the height of each building surface [63]. However, these extrapolations do not account for real-time, localized microclimate variations caused by surrounding urban elements.

CHTC values are critical for estimating the rate of heat exchange due to convection [64]. Tools such as EnergyPlus, IES, and TRNSYS compute CHTCs using inbuilt mathematical models that consider parameters like surface roughness, terrain type, altitude, and wind speed [65]. However, these models frequently fail to accurately capture directional wind variations and the influence of nearby buildings, leading to significant discrepancies in energy performance predictions [66–68].

4.2. Discharge Heat Exchange Modeling

Similar to CHTC, the wind pressure coefficient (WPC) quantifies pressure variations across different building surfaces due to wind flow. WPCs are essential for modeling natural ventilation, air infiltration/exfiltration, and heating and cooling loads. Mathematically, WPCs represent the dynamic pressure difference between external and reference pressures on a building's facade [69].

Several BEM tools, including EnergyPlus and TRNSYS, offer built-in WPC models, allowing users to select an appropriate method based on their specific needs [70]. However, similar to CHTC calculations, these models rely on extrapolated wind data rather than real-time urban wind conditions. Studies have reported significant energy prediction discrepancies when comparing WPC values from CFD-based UMM tools with those generated by standard BEM models. These discrepancies are particularly pronounced in mixed-mode ventilated buildings, where airflow dynamics are more complex and require more detailed microclimate simulations [71–73].

4.3. Radiative Heat Exchange Modeling

Unlike atmospheric heat exchange, radiative heat exchange between building surfaces and surrounding urban elements is not inherently computed by most BEM tools. Among commonly used tools, TRNSYS is the only BEM tool that accounts for radiative heat exchange between surfaces, but only within the building itself [74]. To enable the computation of radiative heat exchange between a building and its surrounding urban surfaces, two key inputs are required: the view factor between the urban and building surfaces, and the hourly temperature data of the urban surfaces [75,76].

BEM tools such as EnergyPlus allow users to model multiple radiative heat exchanges for a given building surface. However, in addition to specifying view factors, users must also manually input the hourly temperature data of all relevant surfaces to activate radiative heat exchange calculations. Alternatively, BEM tools with co-simulation capabilities can perform real-time simulations of surface temperature data and incorporate these values at each computational step for radiative heat exchange calculations. For radiative heat exchange between building and the sky, BEM tools commonly use models developed by Muneer and Perez to estimate shortwave irradiance. Additionally, various models exist for estimating longwave irradiance based on weather file data [77].

5. Review of Existing Integrated Modeling Approaches

Several studies have integrated building energy modeling (BEM) and Urban Microclimate Modeling (UMM) tools to simulate urban microclimate impacts on building energy performance. These approaches can be classified into coupling and chaining methods [16,17]. Coupling involves direct, iterative data exchange between BEM and UMM tools, allowing bidirectional interactions, where building heat contributions influence microclimate simulations and vice versa. Chaining, on the other hand, is a sequential approach where UMM tool outputs serve as inputs for BEM tools without iterative feedback.

From a technical perspective, coupling offers higher accuracy by dynamically integrating BEM and UMM results, yet it remains computationally demanding. CFD-based UMM tools, such as ENVI-Met, lack the capability to incorporate BEM-generated building surface temperature data. While OpenFOAM allows for this integration, its high computational cost makes real-time bidirectional exchange challenging. In contrast, energy balance (EB)-based UMM tools are computationally efficient but fail to accurately capture wind-related parameters, which are essential for modeling both atmospheric and non-atmospheric heat exchanges.

Despite these challenges, integrated modeling approaches have been developed to capture different aspects of urban heat exchange. While some studies focus exclusively on atmospheric heat exchange, others emphasize non-atmospheric radiative interactions between buildings and urban surfaces. The following sections examine the advantages and limitations of these modeling approaches.

5.1. Methods for Modeling Microclimate-Driven Atmospheric Exchanges

Studies modeling atmospheric heat exchange typically modify weather file data or heat transfer coefficients to incorporate localized microclimate effects. As Table 2 shows, among the 30 reviewed studies, 54% revised only weather file data (RoWD), 14% modified heat transfer coefficients (MoHTCs) exclusively, and 21% employed both approaches. Most studies focused on dry bulb temperature (DBT) and relative humidity (RH), while fewer incorporated dew point temperature (DPT), global horizontal radiation (GHR), or direct normal radiation (DNR) [78–81].

Neglecting humidity-related variables can compromise energy performance predictions, as latent heat loads significantly influence cooling and heating demands. Since greenery and water bodies provide evaporative cooling, failing to account for increased humidity levels may lead to miscalculations in building energy savings. Additionally, variations in wind speed and direction must be considered to avoid overestimating or underestimating microclimate impacts on building energy performance.

As mentioned in Section 4.1, conventional BEM tools apply the same weather file data across all building surfaces or extrapolate hourly data, leading to aggregated effects that do not capture localized microclimate variations [63]. Although modifying convective heat transfer coefficients (CHTCs) and wind pressure coefficients (WPCs) improves the

accuracy of heat exchange modeling, these modifications alone cannot fully capture spatiality and seasonality with dynamic microclimatic effects. Studies employing monitored data near the ground or over roofs did not provide a rationale for how they can represent spatial variability.

Despite skepticism about integrating spatially variable microclimate data into BEM tools, a few of previous studies [82,83] have claimed to employ near-surface microclimate data through custom algorithms. Notably, recent versions of EnergyPlus allow users to simulate building energy performance using spatially variable microclimate inputs [84]. However, integrating EnergyPlus with CFD-based UMM tools for fully coupled simulations remains computationally demanding and requires advanced modeling expertise.

Table 2. Multiple UMM and BEM tools employed for modeling atmospheric (convective and discharge) heat exchanges driven by microclimate.

Ref.	UMM Tools/Monitoring	BEM	DBT	DPT	RH	AH	WS	WD	GHR	DNR	CHTC	WPC	RoWD	MoHTCs
[81]	ANSYS Fluent	IDA ICE	x		x		x	x	x	x		x	x	x
[85]	CAT	EnergyPlus	x		x								x	
[86]	CFD	EnergyPlus					x				x	x	x	x
[87]												x		x
[88]		TRNSYS									x		x	x
[89]											x		x	x
[90]	ENVI-met	EnergyPlus	x		x		x				x		x	x
[91]			x		x		x						x	
[92]			x		x		x	x					x	
[93]			Additional information is required											
[94]			Additional information is required											
[95]			x		x		x						x	
[96]		IES-VE	x		x		x						x	
[30]			x		x		x						x	
[80]	ENVI-met + Matlab + Meteonorm	EnergyPlus	x				x		x	x			x	
[78]	ENVI-met and UWG		x	x	x								x	
[97]	GIS-based		x		x								x	
[98]	Monitoring	TRNSYS	x		x		x		x				x	
[79]		EnergyPlus	x		x		x	x	x	x			x	
[99]		IES-VE	x		x		x	x	x				x	
[100]		DeST	x			x	x				x		x	x
[101]	OASUS	IDA ICE	x		x								x	

Table 2. *Cont.*

Ref.	UMM Tools/Monitoring	BEM	DBT	DPT	RH	AH	WS	WD	GHR	DNR	CHTC	WPC	RoWD	MoHTCs
[102]	OpenFOAM	EnergyPlus					x					x	x	x
[103]			x				x				x		x	x
[82]			x				x			Additional information is needed				
[83]			x				x							
[71]												x		x
[104]	OpenFOAM + Lumped thermal models		x				x				x		x	x
[105]	Standards & published models	TRNSYS									x			

5.2. Methods for Modeling Non-Atmospheric Heat Exchanges from Urban Form

Several studies have explored radiative heat exchange between buildings and surrounding urban elements, often using makeshift techniques due to tool limitations. For instance, TRNSYS models streets between buildings as atriums with open ceilings, compensating for its 3D radiation model limitations, which restrict radiative simulations to interior zones. Similarly, earlier versions of EnergyPlus lacked real-time surface temperature updates, leading researchers such as Yang et al. [90] to develop workarounds that integrate actual longwave radiative flux data at building exteriors into the convection heat transfer component. Table 3 provides a summary of these studies, detailing the modeling approaches used for simulating radiative heat exchange.

Table 3. Studies using multiple data sources to simulate radiative heat exchange from contextual urban elements.

Refs.	UMM Tools	BEM	Surrounding Buildings	Ground (Pervious & Impervious)	Grass
[106]	Meteonorm (Grass surface temperature)	CitySim	x	x	x
[82]	-	EnergyPlus	Additional information is required		
[83]	-				
[107]	-		x	x	
[90]	ENVI-met		x	x	x
[104]	Lumped thermal models		x	x	
[74]	-	TRNSYS	x	x	
[108]	-		x		
[105]	-		x		
[88]	-		x		
[59]	-		x		
[89]	CitySim (buildings and sky)		x		

Recent advancements in BEM tools now allow users to simulate road, pavement, and ground surface temperatures concurrently with building energy simulations. Additionally, the introduction of co-simulation frameworks in EnergyPlus enables dynamic surface temperature updates at each simulation step, improving accuracy in non-atmospheric heat exchange modeling. These advancements eliminate the need for workarounds but require expertise in co-simulation techniques and data integration, which remains a barrier to broader adoption.

6. Conclusions

Integrating urban microclimate effects into building energy modeling (BEM) is crucial for accurately simulating energy performance in urban environments. Through a comprehensive review of 94 peer-reviewed studies, this paper systematically evaluates existing urban microclimate-integrated BEM approaches, highlighting their capabilities and limitations. The review first explores the complex interactions between urban form, microclimate, and building energy consumption, followed by an assessment of how BEM tools model these effects.

Findings indicate that CFD-based UMM tools effectively capture the non-linear relationships between urban form and microclimate but remain computationally expensive. Urban microclimate influences buildings through atmospheric heat exchange, encompassing convective and discharge mechanisms, and non-atmospheric radiative heat exchange, which governs interactions between urban surfaces and building envelopes. Integrated modeling approaches, such as modifying weather files and adjusting heat transfer coefficients, provide partial solutions but fail to capture dynamic near-surface microclimate variations. Coupling techniques, which enable bidirectional data exchange between BEM and UMM tools, are preferable to chaining methods, as they better represent real-time microclimate interactions. Recent advancements in BEM tools, such as co-simulation frameworks and spatially variable microclimate integration, support the development of more sophisticated coupling-based approaches. However, challenges remain, particularly the high computational cost of CFD-based UMM tools and their limited ability to efficiently exchange data with BEM platforms. Moreover, a discussion on real-world climate testing and hands-on tool validation to complement computational methods and bridge the gap between simulation and practice is also missing.

To address these limitations, future research must focus on computational efficiency, dynamic microclimate representation, and enhanced data exchange mechanisms. Key areas for development include optimizing numerical methods, integrating machine learning (ML) for predictive modeling, and improving interoperability between BEM and UMM tools. In addition to simultaneous simulation, incorporating ML-based UMM tools allows two-way data exchange with BEM tools, which is a challenge with CFD-based UMM tools. Unlike statistical and empirical UMM tools, ML-based UMM tools can employ future climate projections as forcing data to model the compounded effects of climate change and urban heat island (UHI) impacts on building energy performance.

While the nexus between urban form, microclimate, and building energy performance sets the context for novel readers on this topic, the discussion on the engineering of conventional BEM tools explains the pros and cons of existing systems to modelers. Novel readers can be architects, urban designers, or planners who wish to understand the need for incorporating urban microclimate into building energy performance evaluation and the current scope of integrated modeling approaches in achieving this. Furthermore, pinpointing challenges in traditional integrated modeling approaches, along with the working mechanisms of BEM and UMM tools, serves as a foundation for advancing next-generation urban microclimate-integrated building energy modeling approaches.

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Abbreviations

BEM	Building Energy Modeling
CFD	Computational Fluid Dynamics
CHTC	Convective Heat Transfer Coefficient
DPT	Dew Point Temperature
DBT	Dry Bulb Temperature
DNR	Direct Normal Radiation
GHR	Global Horizontal Radiation
MoHTC	Modification of Heat Transfer Coefficients
RHTC	Radiative Heat Transfer Coefficient
RoWD	Revision of Weather File Data
UBEM	Urban Building Energy Modeling
UHI	Urban Heat Island
UMM	Urban Microclimate Modeling
WPC	Wind Pressure Coefficient

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