EDITORIAL

Interdisciplinary collaborative perspectives: urban microclimate, urban energy systems, and urban building sectors

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Cities are central to global economic and energy activities. By 2023, cities have gathered 56% of the world's population, contributed 80% of the global GDP, and consumed 75% of global energy.[1] While urbanization presents substantial economic benefits and opportunities for social development, it simultaneously poses serious challenges related to climate change, environmental pollution, and energy security. Cities urgently need to transition towards becoming energy-efficient, resilient, and sustainable entities.

Urban meteorological conditions, including temperature, humidity, wind speed, radiation intensity, and pollutant concentration, directly impact daily life and industrial activities. As urbanization advances, distinct microclimate phenomena have emerged within urban micro-scale spaces. Prevalent urban microclimate includes the urban heat island effect, urban wind field effect, urban precipitation effect, urban radiation effect, urban aerosol effect, and urban pollution island effect. Compared to macroscale and mesoscale meteorological changes, urban microclimate evolution exhibits a strong correlation with urban structure and human activities.[2] Key contributing factors include dense clusters of buildings, extensive artificial surfaces, and high-density energy consumption. In urban centers, microclimate manifests as localized phenomena with small spatial and temporal scales, directly influencing human activities and cumulatively impacting the broader climate.[3] The risk of extreme weather events is escalating rapidly due to the combined effects of global warming and deteriorating urban microclimate.

Energy serves as the core foundation of economic prosperity, social stability, and environmental sustainability. Urban energy system integrates the entire energy process, encompassing generation, conversion, transmission, distribution, and consumption. Ensuring the reliability, economy, and sustainability of urban energy supply is the primary goal of energy system resource allocation and operational management. In urban centers, energy demand is characterized by the following distinct features: (1) high-density energy consumption driven by densely populated and economically vibrant areas; (2) significant fluctuations between peak and valley periods; (3) buildings are the main load objects. Consequently, there is a significant spatial correlation between the urban energy network and building distribution. Moreover, more than half of the energy consumed is devoted to heating, ventilation and air conditioning (HVAC) within buildings, indicating that the efficiency of urban energy supply is heavily influenced by meteorological conditions.[4] More seriously, the frequency of extreme weather events in cities, like heat waves, heavy precipitation, and typhoons, exposes urban energy systems to higher levels of uncertainty and damage risk.[5]

The urban building sector comprises all buildings and their associated structures and infrastructure. Buildings include residential, commercial, public, and industrial buildings, serving as a platform for urban functions, cultural expression, and economic development. With growing urban populations and limited land resources, buildings are developing towards high-density and high-rise directions. The entire life cycle of buildings, including design, construction, operation, maintenance, and management, significantly influences the urban environment and energy consumption: (1) dense high-rise buildings disrupt natural wind flow patterns in cities, impeding the dispersion of pollutants and heat; (2) the construction of buildings reduces green spaces, consequently diminishing the urban evapotranspiration capacity; (3) building materials with high reflectivity and heat capacity absorb and retain significant amounts of heat, exacerbating the urban heat burden; (4) high-density energy consumption and pollutant emissions further degrade the urban environment; (5) The building cluster effect further amplifies the pernicious impact of buildings on the surrounding environment and energy consumption, and creates distinct microclimate zones in urban centers. Consequently, urban building design must extend beyond basic functionality and safety, advancing toward sustainability, comfort, and environmental responsibility.

As global warming and urbanization progress, the dynamic interactions between urban microclimate, energy systems, and building sectors within cities are becoming increasingly apparent. There is an urgent need for interdisciplinary approaches to provide scientifically grounded guidance for the construction, management, and renovation of urban areas. Key areas of focus include: (1) Exploring strategies to mitigate the adverse effects of urban microclimates through urban planning, greening initiatives, and innovative building design; (2) Advancing the development of urban energy systems that are more efficient, cleaner, and more reliable; (3) Investigating the application of emerging technologies, such as the Internet of Things (IoT), big data, and artificial intelligence (AI), in enhancing the intelligence and management efficiency of urban systems; (4) Incorporating long-term sustainability strategies in urban planning and development in light of ongoing climate change. Currently, there remains a significant gap in effective interdisciplinary research addressing these critical interactions.

CHALLENGES FOR URBAN ENERGY EFFICIENCY AND CARBON EMISSION MANAGEMENT

The interactions between urban microclimates, urban energy systems, and the urban building sector are intensifying energy consumption and carbon emissions. Typically, the urban heat island effect leads to a surge in cooling demand, while waste heat emissions accumulate around buildings, further elevating urban temperatures. For instance, the cooling electricity demand induced by urban heat island effect markedly increase by up to 40%, and the outdoor air temperature has quantitatively determined to rise by 2.5℃ as a result of using air conditioners.[4] The challenges for urban energy system can be illustrated in two aspects. On the one hand, changes in microclimate conditions significantly impact energy system operations in various ways: increased humidity and pollutant accumulation heighten the need for mechanical ventilation and air purification systems in buildings; heatwaves induce peak loads that require greater system flexibility; high temperatures increase power transmission losses; and hazy weather reduces the energy supply capacity and operational efficiency of solar power systems. On the other hand, building sectors further exacerbate the burden of energy system operation: irrational building design ignores direct sunlight, wind direction and other microclimate conditions, leading to over-reliance on artificial lighting, cooling and heating equipment; high-density building clusters exacerbate the localized heat island effect, further increasing regional energy consumption. To address these challenges, it is essential to consider the synergies among systems comprehensively. Achieving more efficient energy management and reducing carbon emissions require optimized building design, enhanced flexibility in energy systems, and strengthened environmental policy guidance.

CHALLENGES FOR URBAN HEALTH AND SUSTAINABILITY MANAGEMENT

Urban energy systems and building sector activities are significantly contributing to the deterioration of the urban environment. On the one hand, pollutants and waste heat emitted from energy production, transmission, and consumption are primary drivers of urban microclimate deterioration. Coal-fired power stations, as one of the major sources of air pollutants, emission of SO_2, NOx, and PM2.5 accounted for 28.4%, 32.4%, and 7.3% of the total emissions in China, according to the Global Power Emissions Database. The construction of power plants and transmission facilities requires substantial land, altering the thermal capacity and hydrological characteristics. The intensive energy consumption and associated waste heat emissions from air conditioners and heating systems exacerbate urban heat accumulation. Installing large-scale solar and wind power plants, which demand extensive land use, also modifies the thermal capacity and albedo of urban surfaces, contributing to microclimatic changes. On the other hand, the irrational spatial distribution of buildings is a critical factor in the exacerbation of urban microclimate conditions. Activities within buildings further intensify these adverse microclimatic effects. Urban construction often reduces green spaces, thereby diminishing the capacity to dissipate heat through transpiration. High-rise structures and densely packed building layouts disrupt natural wind patterns, resulting in complex variations in wind speed and direction. Building materials with high albedo and heat capacity absorb and store substantial amounts of heat, leading to elevated urban temperatures. In the high-density building center, the mean temperature may exceed 10℃ than the surround rural areas[2].

CHALLENGES FOR URBAN RESILIENCE AND RELIABILITY MANAGEMENT

The deep coupling between urban microclimate, energy systems, and building sector facilitates the transmission of failures across these systems. Cities' heavy reliance on centralized energy supplies renders them vulnerable to severe energy shortages when these facilities are compromised by extreme weather events (e.g., floods, hurricanes). Moreover, high-density building complexes are susceptible to clustering effects during disasters, enabling the rapid propagation of detrimental impacts within the complexes. For instance, heatwaves significantly increase electricity demand, which can lead to power system overloads or localized outages. Additionally, extreme weather events will damage transmission lines and generation facilities, thereby reducing the overall reliability of the energy infrastructure. From 2000 to 2021, over 80% of US power outages were associated with extreme events such as hurricanes, wildfires, heatwaves and flooding.[5] Heavy rainfall can overwhelm building drainage systems or cause roof leaks, while strong winds may inflict damage on windows or facades. From the building sector perspective, the structural vulnerabilities of buildings can trigger cascading effects, including human casualties and property damage. Older buildings exhibit lower resilience to heat, wind, and rain, and their unreliability in the face of increasingly frequent extreme weather events may precipitate secondary disasters. With the intensification of climate change, urban microclimate conditions may undergo long-term changes, such as an increase in average temperature and changes in rainfall patterns. These changes may gradually weaken the expected design performance of urban energy systems and buildings, leading to higher unreliability in addressing climate change.

FRONTIERS ON CROSS-REGIONAL INTERACTION FOR INTERDISCIPLINARY COLLABORATIVE

The coupling between urban microclimate, urban energy systems, and the building sector exhibits significant spatial distributional differences and interactive effects across various urban regions. Factors such as ground cover, building density, and human activities create disparities in microclimate and energy demand within different urban areas. For instance, commercial districts often experience more pronounced heat island effects than residential areas due to higher concentrations of buildings and transportation activities. Consequently, commercial districts tend to have greater cooling requirements compared to residential areas, while industrial areas typically exhibit more diverse energy demands. The propagation of microclimate effects between different urban regions can significantly influence the overall meteorological conditions of the city. For instance, the heat from high-temperature areas may spread to neighboring low-temperature areas, changing the local temperature distribution. Different regions of the city may experience different wind speeds and direction patterns, which can affect the diffusion

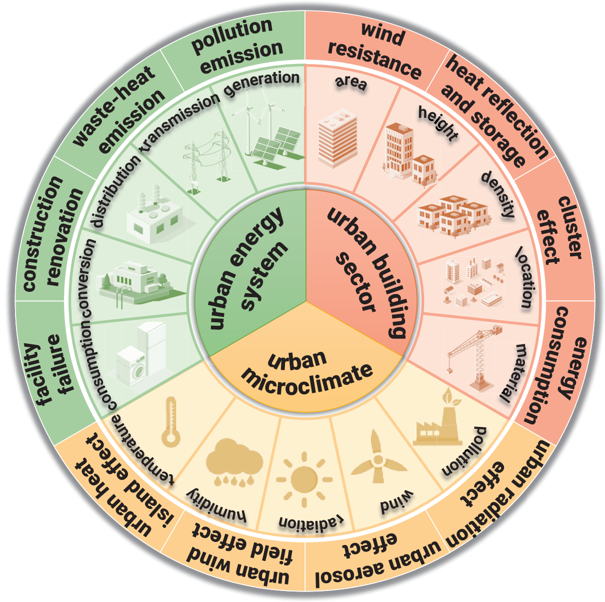

Figure 1. Interdisciplinary collaborative perspectives: urban microclimate, urban energy systems, and urban building sectors.

patterns of heat and pollutants, thereby altering the microclimate conditions in each region. Additionally, changes in precipitation and humidity can modify the city's hydrological cycle, resulting in region-specific microclimate variations. There are significant differences in energy resources and load demands among different regions, and coordinated operations are needed among regions to cope with changes in energy demand and emergency situations.

FRONTIERS ON EMERGING TECHNOLOGIES FOR INTERDISCIPLINARY COLLABORATIVE

In the future, the collaboration between urban meteorology, building engineering, energy management, and urban planning must be strengthened to develop integrated solutions. The development of integrated simulation tools, leveraging technologies such as the Internet of Things (IoT), big data, and artificial intelligence (AI), is essential for supporting both short-term urban operations and long-term planning.

In the building sector, architectural designs should be meticulously tailored to the specific microclimate conditions, thereby reducing energy dependency and enhancing building resilience against extreme climatic events. The spatial arrangement of buildings must account for wind speed and direction to optimize natural ventilation and minimize adverse wind impacts on structures. The development and promotion of energy-efficient building technologies and materials should be prioritized, to achieve optimal energy management through intelligent systems. Phase Change Materials can absorb and release thermal energy, helping to regulate indoor temperatures and reduce the need for heating and cooling. For instance, the UAE University effectively utilizes a natural ventilation system and high-performance building materials, achieving a 30% reduction in cooling demand. Furthermore, the implementation of effective heating, ventilation and air conditioning measures is crucial to maintaining high indoor air quality. Green roofs can reflect more sunlight and absorb less heat, while providing insulation and reducing stormwater runoff.

For energy systems, it is imperative to establish mechanisms for real-time monitoring and adjustment of energy supply and demand, enabling a flexible response to fluctuations driven by urban microclimate changes. Based on sensor and IoT technologies, a virtual digital twin model mapping the physical energy system can be constructed to achieve real-time monitoring, optimized scheduling, fault detection, and performance assessment. Besides, the design and management of distributed energy systems should be explored to ensure the continuity of energy supply and the full utilization of renewable energy sources. For instance, the Los Angeles Climate Action Plan effectively improves urban resilience to extreme weather by promoting renewable energy use, utilizing efficient buildings, increasing green infrastructure, and establishing detection systems. Additionally, energy cascade utilization technologies should be adopted to recover waste heat generated by energy activities. Finally, an environmental impact assessment system for energy systems must be established to evaluate and mitigate the environmental consequences of building sector and energy system activities.

FRONTIERS ON POLICY GUIDANCE FOR INTERDISCIPLINARY COLLABORATIVE

Persistent global warming and urbanization are exposing cities to increased climate risks, health crises, economic downturns, and energy shortages. Interdisciplinary collaboration has become more urgent than ever. However, there are natural barriers to collaboration between urban meteorology, energy systems, and building sectors: (1) conflict of interest: different disciplines have different research goals; (2) knowledge barriers: different technicians have difficulty in communicating and understanding each other effectively; (3) differences in time scales: climate focuses on longer-term trends than building management and energy system operation; (4) lack of integrated platforms and data centers; (5) lack of dedicated funding and incentives. In addressing the above issues, effective policy and support frameworks are key to encouraging collaboration among various stakeholders. For instance, the Government of Singapore has established an urban data platform that brings together various types of data, including meteorological, transportation and architectural data, and facilitates data sharing among researchers from different disciplines. In Finland, the Government regularly organizes interdisciplinary workshops and training to promote exchange and cooperation among urban planners, architects and environmental scientists. The Sustainable Cities Initiative in the United States of America provides a clear policy direction for interdisciplinary collaboration, encouraging cities to collaborate and innovate in areas such as climate adaptation, energy management and building design.

Notably, governments, as facilitators, must anticipate the potential resource, economic, and health inequality risks associated with interdisciplinary collaboration. Specifically: (1) resource inequality: disparities in wealth can result in unequal access to advanced building technologies and energy solutions. This unequal access may exacerbate social divisions, leaving poorer communities at a disadvantage in addressing climate change and urban environmental challenges; (2) economic inequality: low-skilled labor may be excluded from high-end green technologies and sustainable buildings, leading to unequal economic opportunities; (3) health inequality: climate change-induced weather extremes have more significant impacts on low-income and marginalized populations. significant. Therefore, government policies need to introduce equity assessment criteria in interdisciplinary cooperation to ensure that low-income and disadvantaged communities have access to necessary resources and technical support.

FRONTIERS ON FUTURE CITY VISION FOR INTERDISCIPLINARY COLLABORATIVE

Under ongoing global climate change, urban planning, construction, operation and management require more forward-looking approaches to promote efficient, smart, health, sustainable and resilient development. The interdisciplinary collaboration is driving the urban sectors away from being isolated individuals and towards being carriers and standbys for each other.

The future building sector will provide a more efficient, comfortable and sustainable living environment. Smart buildings will provide active and intelligent temperature regulation, shading, ventilation and energy saving based on user habits. Moreover, smart buildings will be integrated with urban meteorological systems, based on big data and artificial intelligence to achieve autonomous learning, forecasting and optimized management. Smart buildings will be integrated with the urban energy system, adjusting short- and long-term energy use and storage based on user behavior and demand, and improving self-sufficiency in extreme weather conditions. Meanwhile, smart buildings will also actively participate in the urban energy trading process, becoming a new type of consumer with the ability to supply and use energy, and improving the overall operational efficiency of the building. In the future, smart buildings will pay more attention to modularization and flexibility, designing flexible spatial layouts to facilitate rapid adjustment and reorganization according to demand.

The future urban energy system will develop towards highly intelligent, distributed and low-carbon. Microgrids composed of distributed energy sources like solar, wind and geothermal energy will be the core of regional energy systems. Hydrogen energy, as a clean secondary energy source, will be widely used in urban transportation, industrial and power systems. Demand-side management and virtual power plant technologies will provide energy managers with a huge pool of flexible resources. Photovoltaic building integration, district cooling and heating, and waste heat recovery and reuse will greatly improve the operational efficiency of energy systems. DC power supply and distribution systems will effectively reduce transmission losses and improve reliability.

With the development of emerging technologies, future cities will become more predictable, sensible and adjustable. Through advanced digital twins, IoT sensing networks, data sharing and collaboration platforms and smart energy management systems, urban micro-meteorological systems, urban energy systems and the urban building sector can realize effective interdisciplinary cooperation to overcome urban development dilemmas.

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DECLARATION OF INTERESTS

The authors declare no competing interests.