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] 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]

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. In urban centers, energy systems are characterized by 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; (4) efficiency of energy supply is heavily influenced by meteorological conditions.[4] Currently, the frequency of extreme weather events, 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. 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; (2) 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; (4) the building cluster effect further amplifies the pernicious impact of buildings on the surrounding environment.

As global warming and urbanization progress, the dynamic interactions between urban microclimate, energy systems, and building sectors 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.

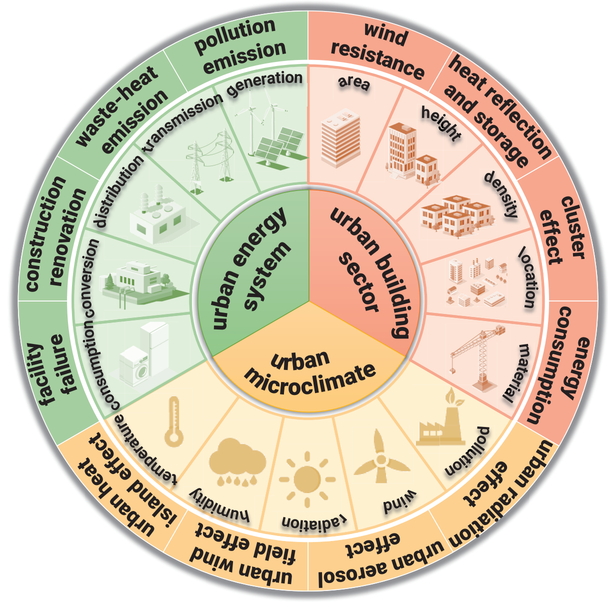

Figure 1. Interdisciplinary collaborative perspectives: urban microclimate, urban energy systems, and urban building sectors.

CHALLENGES FOR URBAN ENERGY EFFICIENCY AND CARBON EMISSION MANAGEMENT

The interactions between urban microclimates, energy systems, and building sectors are intensifying energy consumption and carbon emissions.[4] The challenges can be illustrated in two aspects: On one hand, changes in microclimate conditions significantly impact energy system operations: (1) increased humidity and pollutant accumulation heighten the need for mechanical ventilation and air purification systems; (2) heatwaves induce peak loads that require greater system flexibility; (3) high temperatures increase power transmission losses; (4) 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: (1) irrational building design ignores direct sunlight, wind direction, and other microclimate conditions, leading to over-reliance on artificial lighting, cooling, and heating equipment; (2) high-density building clusters exacerbate the localized heat island effect, further increasing regional energy consumption.

CHALLENGES FOR URBAN HEALTH AND SUSTAINABILITY MANAGEMENT

Urban energy systems and building sector activities are significantly contributing to the deterioration of urban environment. From energy system perspective, pollutants and waste heat emitted from energy production, transmission, and consumption are primary drivers of urban microclimate deterioration. Moreover, 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. From building sector perspective, urban construction 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.[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, heatwaves). These events will damage transmission lines and generation facilities, thereby reducing the overall reliability of the energy infrastructure.[5] Moreover, high-density building complexes are susceptible to clustering effects during disasters, enabling the rapid propagation of detrimental impacts within the complexes. Heavy rainfall can overwhelm building drainage systems or cause roof leaks, while strong winds may inflict damage on windows or facades. 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.

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 IoT, big data, and AI, is essential for supporting both short-term urban operations and long-term planning.

In building sectors, 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. The development and promotion of energy-efficient building technologies should be prioritized, to achieve optimal energy management. The implementation of effective heating, ventilation, and air conditioning measures is crucial to maintaining high indoor air quality. Phase Change Materials can absorb and release thermal energy, helping to regulate indoor temperatures and reduce the need for heating and cooling. Green roofs can reflect more sunlight and absorb less heat, while providing insulation and reducing stormwater runoff.

In 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. For instance, the 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. Additionally, 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 microclimate, energy systems, and building sectors: (1) conflict of interest: different disciplines have different research goals; (2) knowledge barriers: different technicians have difficulty 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.

Notably, governments, as facilitators, must anticipate the potential 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; (2) economic inequality: low-skilled labor may be excluded from high-end green technologies and sustainable buildings; (3) health inequality: climate change-induced weather extremes have more significant impacts on low-income and marginalized populations. 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 be integrated with urban meteorological systems, based on big data and AI to achieve autonomous learning, forecasting and optimized management. It will also 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. Meanwhile, smart buildings will actively participate in the urban energy trading process, becoming a new type of consumer with the ability to supply and use energy.

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.