

Zero Carbon Buildings Under Urban Heat Stress: How Urban Microclimate Redefines Decarbonization Pathways

Shady Attia

Sustainable Building Design Lab, Department of Urban and Environmental Engineering, Faculty of Applied Sciences, Universite de Liege, Belgium, shady.attia@uliege.be

ABSTRACT

Current zero-carbon building (ZCB) frameworks evaluate performance through annual operational energy balance under standardised weather assumptions. However, intensifying urban heat islands (UHI), the mass deployment of air-source heat pumps (ASHPs), synchronised cooling demand, and district-scale thermodynamic interactions challenge the validity of this paradigm in dense urban environments. This paper argues that certified ZCB performance diverges systematically from real urban operational performance because existing frameworks neglect four coupled dimensions: temporal variability of grid carbon intensity, urban microclimate forcing on HVAC efficiency, district-scale system interactions, and pedestrian thermal livability. Three reinforcing feedback loops are identified linking UHI intensity, heat pump COP degradation, and peak-hour grid carbon amplification. The analysis further introduces the emerging heat pump cold island phenomenon at pedestrian level and identifies the absence of coupling between building energy simulation tools and outdoor thermal comfort models as a critical research gap. A reconceptualised four-condition definition of zero-carbon performance is proposed. Results demonstrate that a building certified as net-zero on an annual balance basis can exhibit a 15 to 40 percent performance gap under real urban conditions and may function as a peak-load amplifier rather than a decarbonisation asset.

Keywords: COP degradation, marginal grid carbon intensity, fifth-generation district heating and cooling, pedestrian thermal comfort, aquifer thermal energy storage, Urban Weather Generator coupling

1. INTRODUCTION

The zero-carbon building has become a cornerstone of contemporary building decarbonisation policy globally. Standard ZCB frameworks combine annual energy balance, operational carbon accounting, electrified HVAC systems, on-site renewable generation, highly insulated envelopes, and Typical Meteorological Year (TMY) weather assumptions. These approaches were formulated largely within low-density building contexts where cooling loads were moderate and buildings could reasonably be treated as isolated thermodynamic entities (Attia, 2025).

The rapid densification of urban regions, particularly across East and South Asian megacities, fundamentally disrupts these assumptions. Urban heat island intensities in cities such as Beijing, Shanghai, Chongqing, and Xi'an regularly reach 3 to 8 K above rural surroundings during summer nights, while simultaneously the dominant decarbonisation strategy promotes mass electrification of building heating and cooling via heat pumps. This convergence creates a structural thermodynamic contradiction: the technologies intended to decarbonise buildings increasingly depend on ambient climatic conditions that dense cities are simultaneously degrading.

The present paper is developed within the framework of IEA Annex 89 (Whole-Life Carbon Assessment of Zero Carbon Buildings, 2024 to 2028) and IEA Annex 97 (Sustainable Cooling, 2026 to 2030), which together identify coupled urban thermodynamic performance as a critical knowledge gap in ZCB research. The central argument is that ZCB certification frameworks fail to capture four coupled dimensions: temporal variability of carbon intensity, urban microclimate forcing on HVAC performance, district-scale system interactions, and pedestrian thermal livability consequences. The paper further demonstrates why European low-exergy ZCB solutions are not directly transferable to dense urban contexts such as those prevalent in China.

2. THE PERFORMANCE GAP BETWEEN CERTIFIED AND REAL ZCB PERFORMANCE

2.1 Annual Balance vs. Operational Reality: Three Blind Spots

Current ZCB certification systems evaluate buildings using annualised operational balance under static TMY weather data and averaged grid emission factors. This methodology contains three structural blind spots. First, a time blind spot: annual energy balance conceals hourly carbon spikes, since peak cooling hours coincide with periods when fossil peaker plants are dispatched, producing grid carbon intensities 3 to 5 times the annual average. Second, a space blind spot: UHI adds 2 to 6 K to ambient conditions relative to weather file assumptions, meaning cooling demand is systematically underestimated. Third, a system blind spot: UHI, HVAC, and grid carbon pathways are modelled in isolation, with no tool currently coupling all three domains.

The consequence is a performance gap of 15 to 40 percent between modelled and actual energy consumption depending on building typology, with office buildings showing approximately 28 percent deviation, residential buildings 15 percent, and mixed-use buildings up to 40 percent above the ZCB certification target. Recent work by Amaripadath et al. (2025)

demonstrated precisely this divergence for Belgian net zero energy residential buildings, showing that time-integrated analysis using dynamic grid emission factors reveals net positive carbon emissions during peak periods that annual accounting completely obscures.

2.2 UHI-Induced HVAC Efficiency Degradation

Air-source heat pump COP is highly sensitive to ambient air temperature. Under standard design conditions (outdoor temperature approximately 25 degrees C), a modern ASHP achieves a cooling COP of approximately 4.0. As shown in Figure 1 below, under urban UHI conditions where outdoor temperatures reach 30 to 35 degrees C, the same unit achieves a COP of only 2.2 to 2.9, representing a performance degradation of 27 to 45 percent. This degradation is most severe precisely during peak cooling demand hours, when grid carbon intensity is simultaneously highest, producing a compounding adverse effect on real decarbonisation performance.

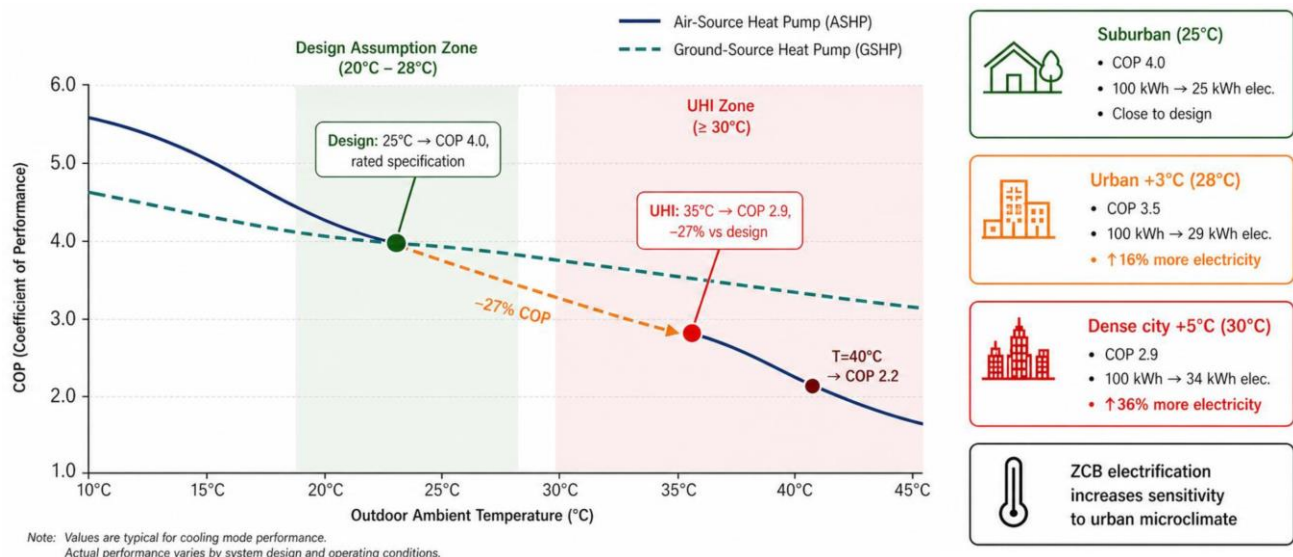


Figure 1. Air-source heat pump COP degradation under UHI conditions. Values are typical for cooling mode; actual performance varies by system and operating conditions (SBD Lab, University of Liege).

At the district scale, the simultaneous operation of thousands of ASHPs generates concentrated anthropogenic heat rejection into the urban canopy layer, further elevating ambient temperatures and deepening the UHI, creating a self-reinforcing thermodynamic feedback loop. Bahadori et al. (2025) evaluated urban heat island mitigation strategies through coupled UHI and building energy modelling and confirmed that HVAC waste heat rejection is a non-negligible contributor to urban heat balance in dense districts.

3. THREE COUPLED THERMODYNAMIC FEEDBACK LOOPS

3.1 Loop 1: The ZCB Efficiency Loop

The first feedback loop directly connects urban warming to building energy performance. Elevated UHI intensity reduces ASHP COP, which increases electricity consumption for equivalent cooling output, which increases total anthropogenic heat rejection into the urban environment, which further elevates ambient temperature. This cycle is reinforcing: each increment of UHI warming produces an increment of additional waste heat discharge, which deepens the UHI. Quantitative estimates place the HVAC contribution to summer urban heat balance at 10 to 20 W per square metre in dense Asian cities, comparable in magnitude to net solar radiation anomalies.

3.2 Loop 2: The Urban Morphology Constraint Loop

Urban morphology determines which ZCB systems are physically possible before a single energy calculation begins. In low- to medium-density European contexts (floor area ratio FAR below 2), aquifer thermal energy storage (ATES), borehole thermal energy storage (BTES), and fifth-generation district heating and cooling (5GDHC) systems can effectively balance seasonal heating and cooling loads. However, in dense high-rise districts typical of Chinese cities (FAR of 3 to 8 and above), subsurface infrastructure congestion, cooling-dominant demand profiles, concentrated heat rejection, and incompatible plot geometries render these systems thermodynamically infeasible. The FAR threshold near 3 constitutes a morphological feasibility boundary: above this threshold, low-exergy system viability deteriorates rapidly, constraining the decarbonisation pathway to high-exergy, cooling-dominant configurations that require sector coupling with industrial waste heat and high-temperature heat pumps operating above 120 degrees C.

3.3 Loop 3: The Grid Carbon Amplification Loop

District-scale electrification of cooling produces synchronised demand spikes that activate fossil peaker generation, elevating marginal carbon intensity precisely when buildings are under maximum thermal stress. In Chinese tier-1 cities, peak summer cooling hours carry marginal emission factors 2.3 to 3.8 times the annual average. The annual net-zero accounting result may therefore conceal peak-hour operational emissions that are substantially positive, fundamentally undermining the real-world decarbonisation claim of ZCB certification. ZCB electrification shifts emissions from annual averages to peak hours, and the annual kWh balance hides the real carbon story.

4. COMPARATIVE ZCB PATHWAYS: EUROPEAN VS. CHINESE URBAN CONTEXTS

The thermodynamic assumptions underlying European ZCB pathways do not transfer to dense East Asian urban environments. Table 1 provides a structured comparison of the key parameters differentiating low-rise European and high-rise Chinese ZCB contexts, synthesised from the SBD Lab research programme and IEA Annex findings.

Parameter	European Context (Low-rise, FAR 0.5-1.5)	Chinese Context (High-rise, FAR 3-8+)
UHI Intensity	+1 to +3 degC typical	+3 to +6 degC summer peak
Design outdoor T.	TMY: 20-28 degC	Actual: 32-40 degC at peak
ASHP COP at peak	3.5-4.0 (close to rated)	2.2-2.9 (27-45% degradation)
Electricity penalty	+16% above rural baseline	+36% above rural baseline
District system	5GDHC / ATES / BTES viable	5GDHC physically fails (FAR > 3)
Subsurface condition	Viable aquifer; balanced H+C	Congested; cooling-dominant
District supply temp.	30-45 degC (low-exergy)	80-160 degC (high-grade heat needed)
Sector coupling	Waste heat from buildings	Industry + data centres required
Peak grid carbon factor	1.5-2.5x annual average	2.3-3.8x annual average (CN grid)
Annual ZCB target	Feasible with current tools	Overestimated: UHI not in TMY
Cold island risk (HP)	Low (dispersed deployment)	High (clustered; pedestrian zone affected)
PET/UTCI impact	Moderate; modellable	Significant; no coupled tool today
A certified zero-carbon building is not zero carbon in a heat-stressed city. Morphology determines feasibility before energy, before technology, before policy.		

Table 1. Comparative analysis of ZCB thermodynamic parameters: European low-rise vs. Chinese high-rise urban contexts.

The city of Xi'an, host of the present conference, exemplifies the challenge. Located in the Guanzhong Basin with a hot-summer/cold-winter climate, the city combines summer UHI intensities of 3 to 6 K with rapid high-rise densification (FAR values commonly exceeding 3.5), creating precisely the conditions under which European low-exergy ZCB assumptions fail. Locally appropriate pathways must integrate industrial waste heat sources, high-temperature district cooling infrastructure, and dynamic carbon-responsive control rather than replicating European passive-house or 5GDHC models.

5. THE MISSING DIMENSION: PEDESTRIAN THERMAL LIVABILITY

5.1 The Heat Pump Cold Island Phenomenon

Mass deployment of air-source heat pumps in dense urban environments generates a hitherto largely unquantified microclimate effect at pedestrian level. While waste heat is rejected at rooftop or facade height (creating a hot zone of +2 to +4 degrees C at 2 to 8 m above ground), large volumes of cooled air are simultaneously extracted near ground level (0 to 2 m), producing a localised cold pool of approximately 2 to 3 degrees C below ambient in the pedestrian breathing zone. This thermal stratification profile is identified in the SBD Lab field investigations as an emerging research frontier.

Beyond temperature effects, HP clustering in urban canyons disrupts airflow patterns, reduces natural ventilation effectiveness and heat flushing, creates humidity pockets with frost risk near ground level, and traps pollutants at pedestrian level through reduced dispersion. The pedestrian thermal comfort impact, measurable via Physiological Equivalent Temperature (PET) and Universal Thermal Climate Index (UTCI), is currently unquantified in any operational policy framework.

5.2 The Tool Coupling Gap

No integrated modelling framework currently couples the three necessary domains: building energy simulation (EnergyPlus, TRNSYS), urban microclimate modelling (ENVI-met, Urban Weather Generator), and pedestrian thermal comfort assessment (PET, UTCI). Standard ZCB certification tools do not accept urban microclimate boundary conditions, and urban microclimate models rarely receive actual HVAC exhaust heat loads as inputs. Coupling TRNSYS with the Urban Weather Generator (UWG) represents the current state of the art, but even this approach does not resolve the cold island to PET/UTCI link. This fragmentation produces a critical research gap: the pedestrian-scale thermal consequences of ZCB HVAC deployment remain systematically unquantified in current policy and design frameworks.

6. FROM BUILDINGS TO URBAN THERMODYNAMIC SYSTEMS

HVAC systems in ZCBs are no longer building components; they are urban climate actors that actively reshape urban heat balance, airflow, humidity, peak electricity demand, and thermal comfort at the street level. The energy-heat-water nexus that characterises urban metabolism must therefore be incorporated into ZCB design frameworks. Heat from UHI raises ambient temperature and COP degrades, increasing electricity demand by 15 to 40 percent. Water, via evapotranspiration and blue-green infrastructure deployment, can reduce peak UHI by 1 to 3 degrees C. District thermal storage integrating waste heat from data centres and industry is essential to balance cooling-dominant loads in dense contexts.

Recent research by Koutra et al. (2026) on fifth-generation district heating and cooling using mine water in Belgium, conducted within the SBD Lab group, confirms that district-scale coupling substantially improves system thermodynamic feasibility relative to building-isolated approaches, while also demonstrating the site-specific nature of such solutions and the impossibility of direct transfer to congested urban subsurface environments. This finding directly supports the morphology threshold argument presented in Section 3.2.

7. TOWARD A RECONCEPTUALISED DEFINITION OF ZERO CARBON

The analysis presented above demonstrates that genuine zero-carbon performance in dense urban environments requires satisfying four simultaneous conditions beyond the current annual energy balance criterion:

(1) Time-dependent carbon accounting. Hourly or minimum seasonal marginal carbon intensity must replace annual averaged emission factors. ZCB must hold at every hour, not just annually. Peak-hour carbon performance must become an explicit certification criterion.

(2) Microclimate-aware performance evaluation. Building energy models must incorporate UHI-corrected weather files derived from urban microclimate modelling rather than rural or airport TMY data. COP degradation under urban heat stress must be reflected in certification simulations.

(3) District-scale system integration. Buildings must be evaluated as nodes within district and infrastructure networks. District thermal storage, waste heat integration, grid flexibility, and sector coupling must be co-optimised. ZCB cannot be solved at the building scale alone.

(4) Thermally livable co-criterion. Outdoor thermal comfort impacts generated by ZCB HVAC systems, quantified via PET and UTCI, must be assessed and bounded as part of zero-carbon certification. Zero carbon must also be thermally livable at pedestrian scale.

This four-condition framework reconceptualises zero-carbon performance not as an isolated building attribute but as a system property of the coupled urban thermodynamic metabolism within which buildings operate.

8. CONCLUSION

This paper has demonstrated that current zero-carbon building frameworks underestimate urban thermodynamic coupling, overestimate real operational decarbonisation, and neglect pedestrian-scale thermal impacts. Three reinforcing feedback loops -- the ZCB efficiency loop, the urban morphology constraint loop, and the grid carbon amplification loop -- systematically undermine the decarbonisation performance of ZCBs in dense urban environments in ways that annual certification metrics cannot detect. The heat pump cold island phenomenon adds a further dimension of thermal livability impact that no current policy framework addresses.

A certified zero-carbon building is not zero carbon in a heat-stressed city. The challenge of building decarbonisation in dense urban environments is not primarily a building-scale problem; it is the challenge of redesigning coupled urban thermodynamic systems. The transition from isolated annual building metrics to urban-scale thermodynamic system design requires collaboration across urban climatology, building physics, HVAC engineering, district energy systems, and urban planning. The International Conference on Urban Climate and Urban Design in Xi'an provides a timely platform for advancing this interdisciplinary agenda.

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