OPEN ACCESS
Energy Systems PERSPECTIVE

Escaping the thermodynamic trap: Decentralized ventilation as a catalyst for urban sustainability

Zhiyong Wu,[1,2,3,*] Chun Chang,[4,*] Mingfei He,[5,6,*] and Dongqiang Lei[1,2,3]

[1]Institute of Electrical Engineering, Chinese Academy of Sciences, Beijing 100190, China
[2]University of Chinese Academy of Sciences, Beijing 100190, China
[3]Key Laboratory of Long-Duration and Large-Scale Energy Storage, Chinese Academy of Sciences, Beijing 100190, China
[4]School of Renewable Energy, Inner Mongolia University of Technology, Ordos 017010, China
[5]School of Energy and Materials, Shihezi University, Shihezi 832000, China
[6]Institute of Bingtuan Energy Development Research, Shihezi University, Shihezi 832000, China
*Correspondence: wuzhiyong@mail.iee.ac.cn (Z. W.); chang21st@126.com (C. C.); mingfei_he@outlook.com (M. H.)
Received: August 25, 2025; Accepted: March 31, 2026; https://doi.org/10.59717/j.xinn-energy.2026.100186

Citation: Wu Z., Chang C., He M., et al. (2026). Escaping the thermodynamic trap: Decentralized ventilation as a catalyst for urban sustainability. *The Innovation Energy* **3**:100186.

China's cities are increasingly caught in a "thermodynamic trap": extreme heat drives rising air-conditioning demand, which in turn intensifies urban heat and further increases cooling loads. This challenge is amplified by the widespread practice of window-opening ventilation during AC operation, which undermines both energy efficiency and indoor air quality control. To address this paradox, fresh-air provision must be decoupled from uncontrolled envelope leakage. Decentralized mechanical ventilation with heat recovery (DMVHR) offers a promising retrofit-oriented pathway by enabling filtered ventilation with reduced thermal penalty. Here, we frame DMVHR not as a standalone remedy, but as a key component of a broader strategy linking building performance, occupant behavior, and urban energy resilience. We argue that, under suitable technical, regulatory, and industrial conditions, large-scale deployment of DMVHR could help reduce peak electricity demand, improve indoor air quality, and support healthier, more sustainable urbanization in China and other rapidly warming regions.

THE URBAN THERMODYNAMIC TRAP

Chinese big cities have engineered themselves into a thermodynamic trap. Building operations generated 2.37 billion tons of CO_2 in 2024, representing 21.4% of national energy-related emissions.[1] More critically, China's 900 million AC units—40% of the global total—create summer peak demands (40-60% of the grid peak loads[2]) that strain grid stability while intensifying urban heat islands through a self-reinforcing feedback loop. At the core of this thermodynamic trap lies a decline in AC efficiency as ambient temperatures rise, described mathematically as:

$$COP(T_{out}) = COP_{ref}(1-\beta(T_{out}-T_{ref}))$$

Where β varies between 0.01 and 0.1 depending on system design. As outdoor temperatures increase from 35°C to 40°C, cooling efficiency can drop by 20-30%, leading to a sharp increase in power consumption. This electricity becomes waste heat dumped into urban environments, elevating ambient temperatures and degrading efficiency further. The recursive relationship governing this escalation can be expressed as:

$$P_{elec} = \frac{Q_{cool}}{COP(T_{amb})}$$

$$T_{amb}^{new} = T_{amb}^{old} + k(P_{elec} + Q_{cool})$$

Where k represents an urban heat accumulation factor and is treated as an effective dynamic parameter reflecting how strongly local urban microclimate responds to anthropogenic heat, depending on urban form, wind conditions, and thermal mass. These expressions illustrate how increased power consumption and rising outdoor temperature mutually reinforce each other: as power usage goes up, waste heat boosts ambient temperatures, which in turn reduces the coefficient of performance (COP) of AC, leading to even higher electricity demand. This is the "thermodynamic trap". Without effective external cooling mechanisms such as wind dissipation, this vicious cycle continuously escalates environmental temperatures until physical or regulatory limits are reached.

This challenge is reaching critical thresholds in megacities such as Chongqing and regions across the North China Plain, where summer temperatures now approach 43°C — the upper operational limits specified by GB/T 7725-2022 for standard AC systems. Under such extreme heat, cooling shifts from a matter of comfort to one of survival, while grid peak loads surge by approximately 6% annually during heat waves, placing infrastructure under severe stress at the very time when reliable cooling is most essential.

THE BEHAVIORAL PARADOX: WINDOW-OPENING DURING AC OPERATION

While China's macro-pathways to carbon neutrality have rigorously addressed envelope efficiency and energy structures,[3-5] they overlook a critical 'thermodynamic leak': occupant behavior in the building sector. Current standards assume sealed, airtight operation, yet this creates a fundamental conflict with the pervasive habit of window-opening for fresh air—a blind spot that decouples design intent from operational reality (Figure 1).

The significance of this issue is underscored by recent data that over 50% of residential buildings and 43% of commercial buildings practice window-opening ventilation during AC operation,[6] increasing cooling loads by 30-60% while allowing outdoor pollutants—including ozone exceeding WHO limits (>200 μg/m^3)—to infiltrate indoor spaces. This behavioral paradox contributes significantly to indoor air pollution, which accounts for 14.1% of China's total disease burden and causes economic losses equivalent to 3.45% of GDP.[7]

Three systemic failures perpetuate this challenge

(1) A primary systemic failure lies in the regulatory blind spot where current frameworks predominantly prioritize natural ventilation, treating mechanical systems merely as supplementary measures. This approach fails to account for the adoption of heat recovery ventilation technologies. Furthermore, the national building energy standard (GB 50189-2015) sets strict criteria for window airtightness yet does not address occupant ventilation behavior or its impact on energy performance. This regulatory framework is based on the assumption that achieving envelope airtightness alone will ensure operational efficiency. In practice, however, lack of guidance on behavioral aspects has led to the common habit of window-opening ventilation during AC operation, leading to substantial cooling-energy penalties in otherwise code-compliant buildings. Although GB/T 51350-2019 promotes centralized heat recovery ventilation, it tends to consume 20-50% of total household electricity, raising cost-effectiveness concerns.[3]

(2) This situation highlights a fundamental behavioral-technological mismatch: whether in winter or summer, residents persist in opening windows to seek perceived 'fresh air,' a habit that conflicts with building energy efficiency requirements amid evolving outdoor environments. Since window-opening ventilation exacerbates heat loss in winter and causes cooling loss in summer, residents face an impossible choice between sealed buildings risking stagnant air or open windows increasing the risk of outdoor-pollution infiltration—with many favoring the perceived freshness of outdoor air despite the associated hidden energy penalties..

(3) Furthermore, an institutional awareness void perpetuates this crisis; public understanding of the severe energy penalties associated with window-opening ventilation during AC operation remains remarkably low, yet no agency currently assumes responsibility for occupant education. The perva-

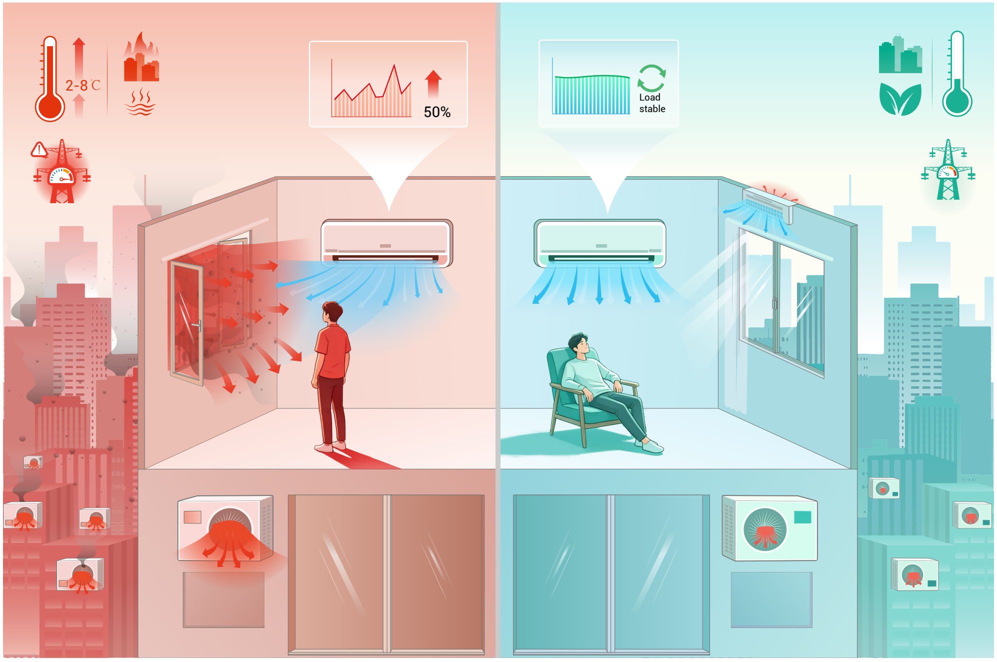

Figure 1. Breaking the thermodynamic trap: From window-opening cooling loss to scalable heat recovery ventilation solution (Left) The vicious cycle: window-opening ventilation during AC operation increases cooling demand and waste-heat discharge, reinforcing urban heat accumulation and grid stress. (Right) A potential pathway: DMVHR supplies filtered fresh air with substantially reduced thermal penalty, helping stabilize cooling loads while supporting indoor air quality.

sive habit of opening windows during AC operation—practiced in over 50% of residential buildings[6]—highlights a limited awareness of the energy implications. At present, no institution—whether building authorities, health agencies, or energy departments—assumes responsibility for occupant education on ventilation behavior impacts.

The combined effects of regulatory blind spots, entrenched occupant habits, and limited institutional engagement contribute to both unnecessary energy loss and avoidable health risks, while also highlighting the need for technological intervention.

DMVHR: A PROMISING RETROFIT-ORIENTED SOLUTION

While centralized mechanical ventilation with heat recovery can partially improve IAQ, its high costs and disruptive ductwork render it economically and practically unfeasible for retrofitting China's vast stock of existing buildings. Moreover, its own electricity consumption, in most cases, further increases overall building energy use.[3]

Compared with centralized heat-recovery ventilation, DMVHR may offer distinct advantages in retrofit settings where duct installation is spatially, economically, or operationally prohibitive. By providing a controlled and filtered fresh-air supply, DMVHR can reduce the perceived and practical need for window-opening ventilation during AC operation, thereby helping to reconcile occupant ventilation needs with energy-efficient building operation. In this sense, it shifts ventilation control from a predominantly system-based paradigm toward a more demand-responsive one. DMVHR should, however, be considered as one component of a broader indoor environmental strategy that may also include improved filtration, airtightness enhancement, occupant education, and climate-specific mixed-mode control. By localizing air exchange and heat recovery at the building envelope, DMVHR can reduce the thermal penalty associated with uncontrolled infiltration and long-distance ducted air transport.

Technical innovation framework

Heat Exchange Mechanisms: DMVHR operates through two proven pathways: recuperative systems (static heat exchangers with parallel airstreams) and regenerative systems (heat-accumulating exchangers with alternating airflow). Modern recuperative systems achieve total heat recovery efficiency of 60–85%, while ceramic and polymer regenerative systems attain sensible heat recovery rates of 80–95%.[8] Technological advancements have pushed the boundaries of aerodynamic and thermodynamic efficiency. The latest generation of decentralized units achieves a critical energy balance:[9] the energy recovered from exhaust air significantly outweighs the electrical energy required for fan operation, with Coefficients of Performance (COP) potentially exceeding 35 under typical winter conditions.[10] This performance suggests that, under suitable conditions, DMVHR can deliver meaningful net energy benefits rather than functioning merely as an auxiliary ventilation device.

Smart Integration Capabilities: Advanced DMVHR units incorporate IoT sensors for real-time monitoring of indoor CO_2, $PM_{2\cdot5}$, VOCs, and temperature, enabling demand-based ventilation that optimizes energy recovery while maintaining IAQ standards. Machine learning algorithms can predict occupancy patterns and adjust ventilation rates, accordingly, reducing unnecessary energy use.

Scalable Implementation: Unlike centralized HVAC retrofits requiring building-wide modifications, DMVHR units install through standard window or wall openings, enabling rapid deployment across China's existing building stock. Manufacturing scalability leverages China's robust industrial capacity for mass production of high-efficiency heat exchangers and control electronics.

Potential system-level implications

Grid Load Reduction: Scenario-based estimates suggest that widespread DMVHR deployment could help reduce summer peak cooling demand, potentially by around 5% at the national scale under favorable adoption assumptions.

IAQ Enhancement: By providing continuous filtered fresh air supply, DMVHR eliminates the false choice between energy efficiency and air quality that drives window-opening behavior. Field studies demonstrate 60-80% reductions in indoor $PM_{2\cdot5}$ concentrations compared to natural ventilation.

Health Co-benefits: Improved IAQ through DMVHR deployment could generate meaningful public-health co-benefits by reducing pollutant exposure and associated healthcare and productivity losses.[7]

POLICY PATHWAYS AND IMPLEMENTATION STRATEGY

Technological readiness and manufacturing scale-up

Quality Assurance Standards: Ensuring effective DMVHR deployment requires rigorous product certification aligned with international standards (EN 13141-7 for residential ventilators). China's manufacturing ecosystem must prioritize heat recovery efficiency verification, acoustic performance testing, and long-term durability assessment to build market confidence.

IoT Integration and Smart Controls: Advanced DMVHR systems leverage Internet of Things technology for demand-responsive operation, automatically adjusting ventilation rates based on IAQ sensors and occupancy patterns. This intelligent control prevents energy waste from unnecessary ventilation while maintaining optimal IAQ standards.

Cost Reduction Through Scale: The economic viability of DMVHR may follow learning-curve dynamics similar to those observed in other manufactured clean-energy technologies. Leveraging established industrial supply chains for motors and heat exchange materials, the marginal cost of deployment is projected to decline rapidly. This affordability is crucial not for market dominance, but for equity: it renders high-performance ventilation accessible to the mass market, enabling the retrofitting of vast existing building stocks that are currently locked in the low-efficiency window-opening cycle.

Regulatory framework evolution

Building Code Integration: A high-impact policy option would be to incorporate DMVHR or equivalent high-performance ventilation solutions into residential and commercial building codes, particularly in climates and building types where window-opening during AC use imposes substantial energy and IAQ penalties.

Beyond regulation, the deployment of financial incentive mechanisms, such as tax credits and utility rebates, can accelerate adoption in existing buildings. Pilot programs in high-pollution cities like Beijing and Shanghai could demonstrate health and energy benefits, building political support for nationwide deployment.

Professional Training Programs: Large-scale DMVHR implementation requires trained installers and maintenance technicians. Professional certification programs ensure proper installation and long-term performance, while creating employment opportunities in the growing clean technology sector.

Public awareness and behavioral change

Educational Campaigns: Comprehensive public education should highlight the dual benefits of DMVHR: measurable energy and IAQ benefits compared to window-opening ventilation. Social media campaigns, building energy labeling, and utility bill messaging can raise awareness of ventilation behavior impacts.

Demonstration Projects: High-visibility installations in government buildings, schools, and public housing can showcase DMVHR benefits while providing real-world performance data. Early demonstration evidence from early adopters will drive wider adoption and technology refinement.

GLOBAL IMPLICATIONS AND FUTURE OUTLOOK

The paradigm of DMVHR technology extends far beyond China's borders, offering a scalable solution to the global building energy-climate nexus. As extreme heat events intensify worldwide, the thermodynamic trap afflicting Chinese cities will emerge in megacities across Asia, Europe, and North America. Countries experiencing rapid urbanization can learn from China's experience, deploying DMVHR proactively rather than reactively addressing energy-IAQ crises.

Future R&D should focus on the integration of aerodynamics, functional materials, and intelligent control to overcome current barriers to large-scale adoption. Advances in fan geometry, particularly crossflow configurations, are needed to deliver high airflow rates with minimal noise, a prerequisite for acceptance in residential environments. At the materials level, priority should be given to developing multifunctional materials or membranes capable of recovering both heat and moisture. When coupled with AI-driven predictive algorithms for demand-based ventilation control, these innovations could shift ventilation components from passive devices to active, energy-responsive nodes within the smart grid.

Furthermore, the anticipated growth in manufacturing creates opportunities for international technology transfer and knowledge sharing. Developing nations facing similar urban heat island challenges could benefit from Chinese experience in policy integration, manufacturing scale-up, and public awareness campaigns.

Global DMVHR deployment could contribute significantly to international climate commitments. Scenario-based estimates suggest that widespread adoption could reduce building sector emissions by 8-12%, supporting Paris Agreement objectives while improving urban livability and public health.

CONCLUSION: SEIZING THE THERMODYNAMIC OPPORTUNITY

China's building sector stands at a critical inflection point. As climate pressure, energy security concerns, and urban air-quality challenges converge, the thermodynamic trap described here is becoming increasingly difficult to ignore. At its core lies a persistent disconnect between sealed-building energy logic and occupants' continuing need for fresh air. DMVHR offers a promising means of reducing this mismatch by enabling filtered ventilation with a much lower thermal penalty than window-opening ventilation during AC operation.

Its large-scale value, however, will depend on more than technical feasibility alone. Continued progress in product design, heat-and-moisture recovery, acoustic performance, intelligent control, and installation quality must be matched by supportive policy frameworks, robust certification systems, professional training, and stronger public awareness. DMVHR should therefore be viewed not as a universal solution, but as one component of a broader strategy for healthier, more energy-efficient buildings.

Because of its dense urban building stock, strong manufacturing base, and growing exposure to extreme heat, China provides a particularly important setting in which to test whether such a pathway can be scaled in practice. Success in this context could offer useful lessons for other rapidly urbanizing regions facing similar tensions among cooling demand, indoor air quality, and climate resilience.

REFERENCES

1. Building Energy Research Center of Tsinghua University. (2025). Annual Development Research Report on Building Energy Efficiency in China 2025. China Urban Science Research Association ed.
2. Yue M., Qiu Z., Wu K., et al. (2024). Research on aggregation regulation process for large-scale air conditioning load. *Power Demand Side Manag.* **26**:41–47. DOI:10.3969/j.issn.1009-1831.2024.03.007
3. Jiang Y. and Hu S. (2021). Paths to carbon neutrality in China's building sector. *Heat. Ventilat. Air Condit.* **51**:1–13. DOI:10.19991/j.hvac1971.2021.05.001
4. Xu W., Ni J., Sun D., et al. (2021). Research on the Target Decomposition and Path of Building Carbon Peak and Carbon Neutrality in China. *Heat. Ventilat. Air Condit.* **37**:1–8. DOI:10.13614/j.cnki.11-1962/tu.2021.10.01
5. Zhuang W., Liu J., Wang J., et al. (2023). Key frontier basic science issues in building carbon neutrality. *Bull. Nation. Nat. Sci. Found. China* **37**:348–352. DOI:10.16262/j.cnki.1000-8217.2023.03.010
6. Yao M. and Zhao B. (2017). Window opening behavior of occupants in residential buildings in Beijing. *Build. Environ.* **124**:441–449. DOI:10.1016/j.buildenv.2017.08.035
7. Liu N., Liu W., Deng F., et al. (2023). The burden of disease attributable to indoor air pollutants in China from 2000 to 2017. *Lancet Planet. Health* **7**:e900–e911. DOI:10.1016/S2542-5196(23)00215-2
8. Alonso M.J., Liu P., Mathisen H.M., et al. (2015). Review of heat/energy recovery exchangers for use in ZEBs in cold climate countries. *Build. Environ.* **84**:228–237. DOI:10.1016/j.buildenv.2014.11.014
9. Merzkirch A., Maas S., Scholzen F., et al. (2016). Field tests of centralized and decentralized ventilation units in residential buildings – Specific fan power, heat recovery efficiency, shortcuts and volume flow unbalances. *Energy Build.* **116**:376–383. DOI:10.1016/j.enbuild.2015.12.008
10. Aristov Y.I., Mezentsev I.V. and Mukhin V.A. (2008). A new approach to regenerating heat and moisture in ventilation systems. *Energy Build.* **40**:204–208. DOI:10.1016/j.enbuild.2007.02.029

FUNDING AND ACKNOWLEDGMENTS

This work was supported by the National Natural Science Foundation of China (Grant No. 52293415), the Shihezi University High-Level Talents Research Start-up Fund Program (RCZK2025108) and Zhengzhou Aerotropolis Institute of Artificial Intelligence. Sincere gratitude is extended to Y.I. Aristov, I.V. Mezentsev and A.A. Chernov from the Siberian Branch of the Russian Academy of Sciences, Jiandong Li from China Academy of Building Research Co., Ltd., Yuanyuan Li from Wuhan University of Technology， as well as E. Juraev and J.S. Akhatov from the Physical-Technical Institute of Uzbekistan Academy of Sciences, for their valuable discussions and insightful suggestions. The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

AUTHOR CONTRIBUTIONS

Zhiyong Wu: Writing – original draft, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. Chun Chang, Mingfei He, Dongqiang Lei: Writing – review & editing, Visualization, Formal analysis. All authors contributed to the manuscript and approved the final version.

DECLARATION OF INTERESTS

The authors declare no competing interests.