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Toward Enhancing Building Thermal Resilience through Passive and Envelope-Integrated Strategies under Climate Extremes and Building Electrification

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Against the backdrop of increasingly frequent extreme climate events and accelerated building electrification, research on building envelopes is shifting from static thermal insulation and annual energy consumption optimization toward the enhancement of building thermal resilience under disturbance scenarios. The key focus is no longer on optimal energy efficiency under normal operating conditions, but rather on whether a building can rely on its own thermal response to delay indoor environmental degradation and maintain thermal safety, habitability, and basic thermal services under conditions such as heatwaves, cold spells, power outages, load shedding, and unstable external energy supply. Accordingly, the building envelope should no longer be regarded merely as a passive boundary that impedes heat flow, but rather as an integral carrier of the building's own fabric, capable of heat gain, heat storage, heat regulation, and thermal buffering. Correspondingly, building-integrated thermal storage should not be confined to short-cycle heat storage for diurnal fluctuations but should further serve long-term thermal safety assurance under scenarios involving consecutive heatwaves, prolonged cold spells, and constrained energy supply.[1] The building thermal resilience discussed in this paper encompasses not only the passive resistance and buffering of heat flow by the building envelope, but also the harvesting, storage, and utilization of heat by the envelope and its integrated systems in pursuit of thermal safety objectives. Furthermore, it includes autonomous support provided by building-integrated self-sufficient energy systems, when necessary, thereby maintaining thermal safety, habitability, and basic thermal services under conditions of unstable external grid or energy supply. Considering this paradigm shift, this paper begins with the evolution of research paradigms for building envelopes oriented toward thermal resilience and further discusses pathways for enhancing building thermal resilience under extreme disturbance scenarios, so as to address the new challenges posed by the intensification of extreme climates and accelerated building electrification.

PRACTICAL DRIVERS OF THIS RESEARCH SHIFT

This research shift is jointly driven by the intensification of external disturbances and the reconfiguration of building operation modes. On the one hand, building boundary conditions have shifted from relatively stable conventional meteorological conditions to thermal disturbances characterized by persistence, abruptness, and compound nature – such as prolonged heatwaves, sustained cold spells, and highly fluctuating weather. Against this backdrop, the function of the building envelope is no longer confined to thermal insulation and energy conservation under normal operating conditions but is further endowed with the responsibility of delaying indoor environmental degradation, buffering thermal shocks, and ensuring thermal safety during extreme events. On the other hand, as building electrification continues to … of cooling, heating, ventilation, and domestic hot water services on external energy supply and the stable operation of electromechanical systems has deepened considerably. Grid fluctuations, power outages, load shedding, or system failures can directly compromise a building's ability to maintain thermal safety and basic thermal services. Consequently, whether a building can rely on the thermal inertia, thermal storage capacity, and self-sufficient energy support capability of its envelope and integrated systems to sustain basic thermal conditions and services under

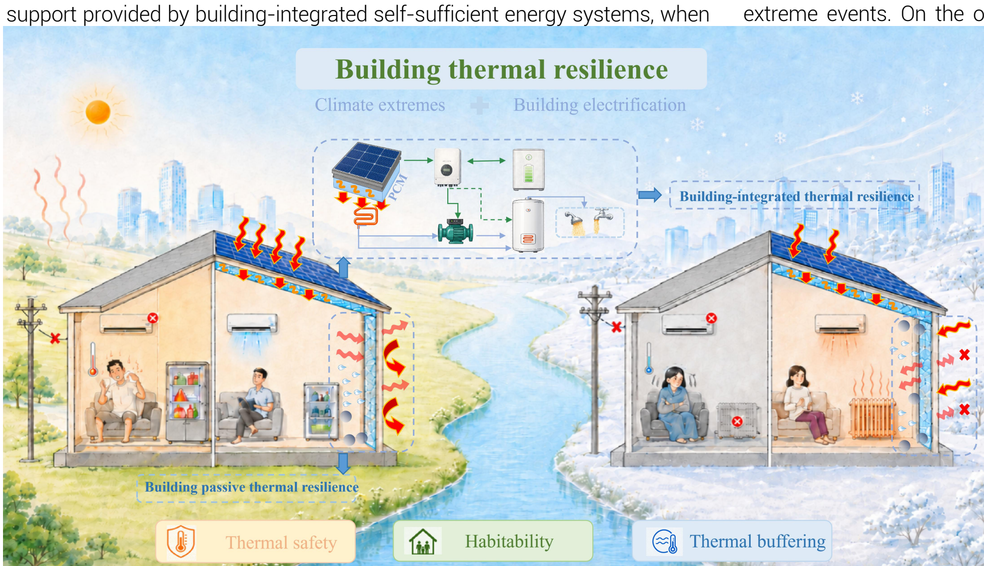

Figure 1. Dual-pathway enhancement of building thermal resilience: passive envelope enhancement and envelope-integrated self-sustaining energy synergy

conditions of constrained or interrupted external energy supply has become a key measure of building thermal resilience. This research shift is not a mere extension of energy efficiency goals, but an inevitable outcome of the combined effects of intensifying climate change, increasing frequency of extreme events, and the heavy dependence of building operation on external energy supply.[2]

CURRENT LIMITATIONS AND KEY CHALLENGES

Although considerable progress has been made in research on building envelope energy efficiency, the existing research system remains largely grounded in steady-state heat transfer and normal operating conditions, thus providing insufficient support for building thermal resilience. First, current evaluation frameworks predominantly focus on metrics such as thermal transmittance, thermal resistance, annual energy consumption, and peak load, yet lack assessment methods that can directly characterize the duration of thermal safety maintenance, rates of indoor environmental degradation, passive buffering effectiveness, and the sustainability of basic thermal services during extreme events. Second, existing studies tend to narrowly interpret thermal storage as the enhancement of material-level heat retention performance, with insufficient attention to the synergistic mechanisms governing the whole process of heat harvesting, storage, and utilization at the building scale. There is a lack of systematic understanding of the mechanisms for transporting, dispatching, and end-using stored heat, which hinders the conversion of material-level or component-level thermal storage potential into tangible thermal resilience benefits. Third, for photovoltaic-integrated envelope systems, current research mainly focuses on power generation gains and conventional energy efficiency improvements, with limited attention to waste heat recovery, long-term thermal storage, thermal service assurance, and autonomous response capabilities under external grid instability. Therefore, research on building envelopes urgently needs to shift from mere material performance optimization toward thermal resilience design that addresses building scale, extreme scenarios, and system integration.

TECHNOLOGICAL PATHWAYS AND FUTURE PROSPECTS

To address issues such as indoor overheating, cooling system failure, and interruption of domestic hot water caused by the combined effects of heatwaves and power outages, as well as indoor overcooling and lack of hot water resulting from heating system failure during consecutive cold spells, the future enhancement of building thermal resilience can be pursued at two levels. The first level involves directly improving the thermal resilience of the passive building envelope, enhancing thermal safety, habitability, and thermal buffering capacity through heat gain, storage, and utilization. The second level couples the thermal resilience enhancement of the passive building envelope with building-integrated photovoltaic self-generation and associated electricity storage, thereby forming an autonomous response system based on the synergy between thermal storage and electrical storage, which improves the capability to ensure thermal safety and basic thermal services under unstable external energy supply conditions.

Technical Pathway one: A building-integrated thermal storage pathway based on “smart optically and thermally responsive exterior skin – gradient thermally conductive phase-change thermal storage – synergistic enhancement of thermal, humidity, and air quality” for exterior walls. For the wall envelope, a multi-layered, synergistic building-integrated thermal storage system can be constructed from the exterior to the interior. On the exterior side, a smart optically and thermally responsive skin with adaptive responsiveness to temperature and solar radiation is developed, which enhances reflection and radiative cooling under heatwave conditions to reduce envelope heat gain, and enhances solar heat capture and utilization under cold conditions.[3] On the interior side, a composite material system integrating thermal storage and release, humidity buffering, and pollutant adsorption/degradation is developed, and through structural design, a phase-change thermal storage structure with adaptive heat flow regulation is formed. On this basis, a gradient thermally conductive network with increasing thermal conductivity from the exterior to the interior can be further constructed, establishing a mechanism for directional heat transfer and staged thermal response. Under heatwave scenarios, the exterior layer mitigates external heat input, while the interior layer absorbs and stores indoor excess heat; combined with natural ventilation at night, a “cool storage – cool use” cycle is achieved, thereby delaying indoor overheating. Under cold scenarios, the exterior layer enhances solar heat gain, and the interior thermal storage units store and slowly release the harvested heat to reduce indoor temperature fluctuations and improve passive thermal security without external heating supply. Simultaneously, this pathway can synergistically enhance indoor air quality through coupled thermal-humidity regulation and the adsorption/degradation of pollutants such as PM2.5.[4]

Technical Pathway two: A building thermal resilience pathway for roofs based on “photovoltaic-coupled waste heat recovery and storage – autonomous thermal service assurance.” For the roof envelope, particularly building-integrated photovoltaic systems, a building-integrated thermal resilience system integrating waste heat recovery, thermal storage utilization, domestic hot water supply, and emergency support can be established. The core objective is not merely to increase power generation, but to rely on the photovoltaic-coupled system to form autonomous assurance capabilities through the synergy between thermal storage and electrical storage, enabling the building to maintain basic thermal services under conditions of unstable external grid or energy supply. Specifically, a transparent thin film with simultaneous spectral regulation and thermal management functions can be developed. On the backside of the photovoltaic module, a phase-change material with high thermal conductivity and high thermal storage density is integrated to achieve rapid absorption, conduction, and storage of waste heat, thereby suppressing module temperature rise and enhancing system stability. The stored heat can be transferred via heat exchange pipes to a water heater or thermal storage tank for domestic hot water supply and further used for building heating terminals. Under scenarios of external energy supply interruption, the pre-stored heat can be prioritized for maintaining thermal safety and basic thermal services. Additionally, a small-scale thermoelectric conversion device can provide emergency electricity to sustain critical low-power loads such as fans and controllers.[5]

Overall, future research should focus on the entire process of “heat harvesting – storage – release – utilization” within the building itself, integrating efficient energy harvesting, long-term on-site storage, and on-demand controllable release. This will drive the transformation of the building envelope from a passive boundary into a composite functional system capable of harvesting, buffering, regulating, and supporting basic thermal services.

CONCLUSION

Against the backdrop of intensifying extreme climates and accelerating building electrification, research on building envelopes is shifting from static thermal insulation and conventional energy efficiency toward building thermal resilience centered on thermal safety maintenance, thermal buffering enhancement, and disturbance adaptation. The key focus is no longer the isolated pursuit of optimal material parameters or conventional energy performance, but rather the synergistic coupling of high-performance materials, envelope construction, on-site thermal storage, and basic thermal services under compound scenarios such as heatwaves, cold spells, power outages, and load shedding, thereby establishing a composite envelope system capable of heat harvesting, storage, regulation, and utilization. Under this paradigm shift, building thermal resilience should no longer be narrowly understood as the passive resistance and short-term buffering of heat flow by the envelope; rather, it should be further extended to encompass the ability of the building envelope and its integrated systems to harvest, store, and utilize heat in pursuit of thermal safety objectives, and to rely, when necessary, on building-integrated self-sufficient energy support to ensure the continuity of basic thermal services. Consequently, the building envelope will no longer serve merely as a thermal flow boundary between the building and the external environment but will become an essential built-in carrier underpinning thermal safety assurance, continuity of thermal services, and adaptive capacity to extreme scenarios.

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DECLARATION OF INTERESTS

The authors declare no competing interests.