OPEN ACCESS
Energy Storage PERSPECTIVE

Unlocking solar cooling potential with absorption thermal battery

Zhixiong Ding,[1,2] Yunren Sui,[1,2] and Wei Wu[1,2,*]
[1]School of Energy and Environment, City University of Hong Kong, Hong Kong SAR, China
[2]City University of Hong Kong Shenzhen Research Institute, Shenzhen 518057, China
*Correspondence: weiwu53@cityu.edu.hk
Received: August 11, 2025; Accepted: September 25, 2025; Published Online: July 16, 2026; https://doi.org/10.59717/j.xinn-energy.2026.100166

Citation: Ding Z., Sui Y. and Wu W. (2026). Unlocking solar cooling potential with absorption thermal battery. *The Innovation Energy* **3**:100166.

Since solar irradiance and cooling demand often exhibit temporal synergy, the vision of using solar energy to meet cooling needs has long been regarded as a promising pathway for low-carbon cooling. However, practical deployment remains limited due to several critical challenges: poor reliability stemming from the intermittency of solar energy, low overall efficiency resulting from multiple energy conversions, and increased system complexity and cost due to the need for numerous interconnected components and sophisticated control systems. This study briefly analyzes the existing technologies related to solar cooling technologies, encompassing solar conversion, energy storage, and various cooling methods. Then, we introduce the concept of the absorption thermal battery (ATB), i.e., integrating energy storage and cooling into a single unit. Driven by low-grade solar thermal energy (e.g., 50-60 °C) and operating with zero-GWP working fluids (e.g., H_2O/LiBr, NH_3/H_2O), ATB delivers exceptionally high energy storage density (over 300 kWh/m^3 with H_2O/LiBr), enabling a compact system architecture with minimal thermal losses, and also enhances energy security and structural safety. Furthermore, the key advantages and challenges for scaling solar-driven ATB are identified from multiple perspectives. This study aims to propose a promising pathway for advancing solar cooling technologies, with the goal of unlocking its full potential and providing theoretical insights and inspiration for future research in this field.

EXISTING TECHNOLOGIES RELATED TO SOLAR COOLING

The utilization of solar energy represents a critical pathway to alleviating the energy crisis and environmental challenges, as well as achieving carbon neutrality targets. Currently, solar photovoltaic and solar thermal technologies are the two predominant approaches. In contrast, although the demand for cooling is particularly pronounced in regions with abundant solar resources, solar cooling systems remain rare in practical engineering applications. A key challenge lies in the fact that solar energy, once collected, cannot be directly converted into low-temperature cold energy, necessitating an additional refrigeration device. This requirement increases both the complexity and cost of solar cooling systems. Furthermore, the intermittent and variable nature of solar energy makes it inherently difficult to align with the dynamic cooling demand, thereby requiring an energy storage unit to effectively bridge the gap between solar energy supply and cooling demands.

Accordingly, a basic solar cooling system typically comprises three key components: a solar energy collection and conversion unit, an energy storage unit, and a cooling device, as illustrated in Figure 1A. Whether solar energy is converted into heat or power, there are existing technologies for subsequent heat and electricity storage, as well as for both thermally and electrically driven cooling. Notably, the energy storage unit can be positioned either upstream of the cooling device to buffer the fluctuations of solar input, or downstream, by storing and regulating the cooling output to meet user demand more reliably. While a wide range of technologies appear to be available for solar-driven cooling, truly self-sufficient solar cooling systems for small-scale residential or single-building applications remain uncompetitive in the market. Apart from grid-powered solar cooling, which bypasses the need for on-site solar conversion and energy storage, standalone solar cooling systems continue to face major barriers, including high costs and low overall efficiency.

To better understand these challenges, it is necessary to briefly analyze the key technologies underpinning solar cooling, including solar conversion, energy storage, and cooling methods. Solar conversion for cooling primarily relies on two mature technologies: photovoltaic (PV) panels and solar thermal collectors. PV panels convert solar radiation into electricity with wide applicability and rapid global deployment, while solar thermal collectors directly provide heat with high efficiency and cost-effectiveness,[1] making them suitable for distributed heating and cooling. To address the intermittency of solar energy, electric battery and thermal battery are employed. Electric battery offers flexibility but faces cost, safety, and lifespan challenges. Thermal battery, including sensible and latent storage, enables coupling with solar thermal systems for cooling, though it suffers from heat loss and limited energy storage density (ESD).[2] Current solar cooling mainly adopts vapor-compression chillers powered by PV electricity or absorption chillers driven by solar heat. While widely studied, both approaches face barriers to large-scale adoption due to system complexity, high capital costs, and limitations of existing storage systems. Emerging cooling technologies (e.g., thermoelectric, thermoacoustic, thermoelastic, electrocaloric, or magnetic cooling) show promise but remain at early stages of development for space cooling.

In this study, after the brief analysis of various technologies related to solar cooling, we highlight the significant potential of the emerging solar-driven absorption thermal battery (ATB) in advancing solar cooling applications. Moreover, we further discuss the advantages and challenges associated with the deployment of ATB from multiple perspectives.

SOLAR COOLING WITH ATB

ATB has emerged as a transformative approach, enabling ultrahigh ESD exceeding 300 kWh/m^3,[3] far surpassing conventional sensible and latent thermal batteries. ATB stores heat as chemical potential in binary solutions (e.g., H_2O/LiBr), where the concentration gradient remains stable indefinitely with negligible thermal losses. As shown in Figure 1B, solar collector drives desorption of the refrigerant (solvent) from the solution during the charging process, with subsequent condensation in the refrigerant tank. This process increases solution concentration, storing thermal energy as chemical potential in the form of a concentration gradient. During the discharging process, the concentrated solution absorbs refrigerant vapor to maintain system vacuum pressure, enabling continuous evaporation of liquid refrigerant, thereby producing cooling output. Unlike traditional thermal battery systems that only discharge heat with heat input, ATB uniquely integrates energy storage and cooling functions: the stored concentration potential can directly drive refrigeration without additional cooling devices.

In addition, annual simulation results indicate that solar-driven ATB can achieve exceptionally high cooling met ratio across cities at different latitudes and climatic zones (Figure 1C), i.e., the highest cooling met ratio of 0.94 was achieved in Singapore.[4] This indicates that ATB is not limited to a narrow range of conditions but holds broad applicability. Thus, ATB presents an ideal solution for solar cooling systems, combining high ESD and near-lossless storage capabilities for extended, even seasonal, thermal storage.

Advantages

Figure 1D illustrates the various advantages of solar cooling with ATB, which demonstrates multifaceted advantages over prevailing PV-driven vapor-compression cooling and thermally-driven absorption chillers.

Zero-GWP working fluids. H_2O/LiBr and NH_3/H_2O remain the most widely adopted working fluids in current ATB systems. Owing to their negligible GWP, they effectively address the replacement challenge associated with the high-GWP fluorocarbon refrigerants traditionally used in vapor-compression cooling systems.

High energy storage performance. Recent advances in ATB cycle design have markedly improved both ESD and overall system efficiency, while simultaneously reducing the charging temperature. Conventional ATB configurations typically require charging temperatures in the range of 80-95 °C. Under

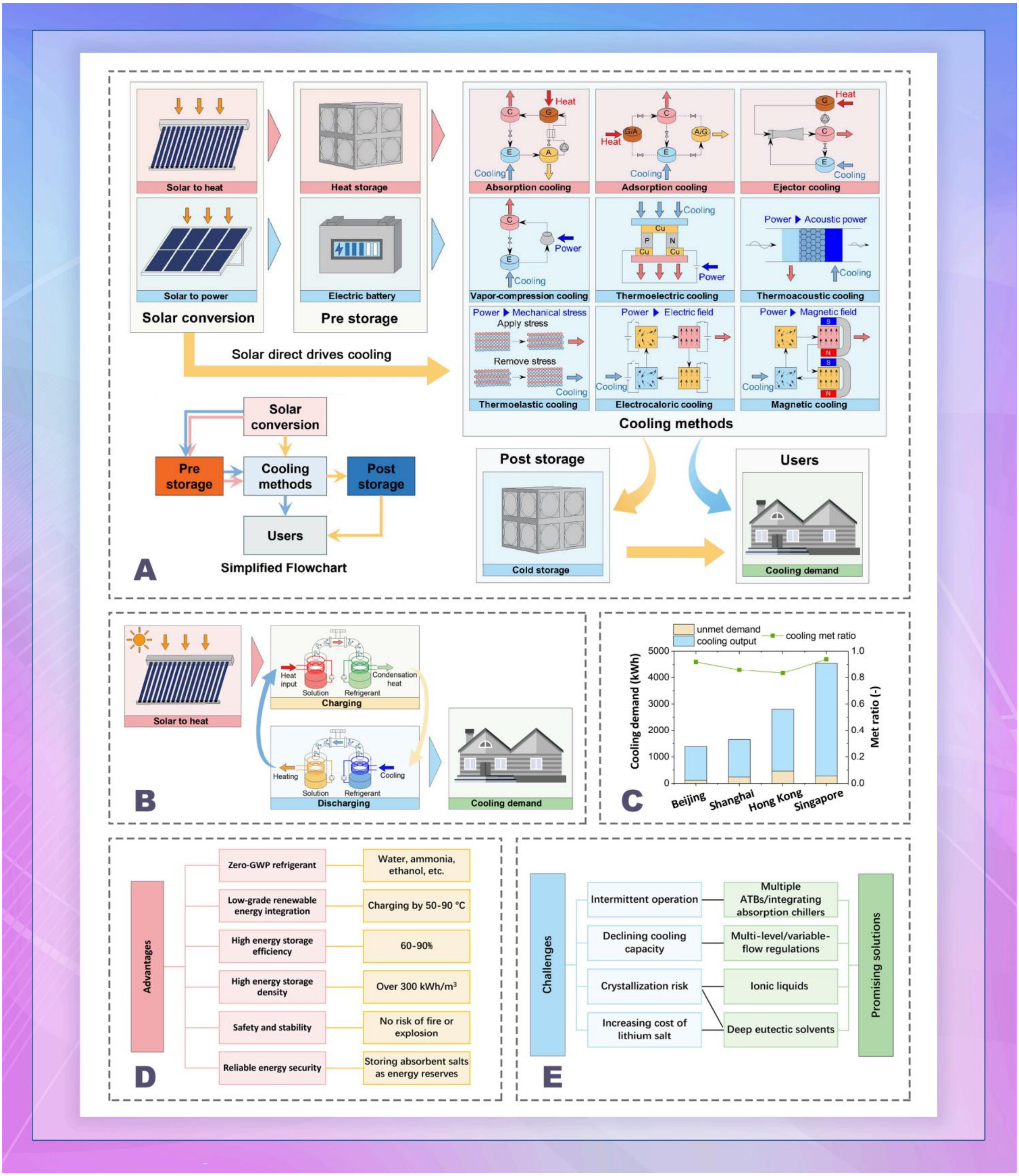

Figure 1. (A)Flowchart of various solar cooling technologies. Comprehensive evaluation of solar cooling with ATB. (B) schematic of working principle and process flow, (C) annual cooling met ratio across cities at different latitudes, (D) advantages, (E) challenges and their corresponding promising solutions.

conditions of low solar irradiance, such elevated thresholds are difficult to maintain, often resulting in partial charging and severe performance degradation. In contrast, emerging concepts such as compression-assisted and two-stage ATB cycles demonstrate stable and efficient operation with heat sources as low as 50-60 °C.[5] By effectively lowering the barrier for system activation, these innovations significantly expand the feasible operating envelope of ATB technology, thereby enhancing its adaptability to diverse climatic conditions and reinforcing its potential for solar cooling applications.

Integration of storage and cooling. PV-driven refrigeration systems, requiring separate electric batteries and chillers, exhibit significantly higher levelized costs compared to integrated ATB modules that combine energy storage and cooling functionalities. Furthermore, battery degradation further amplifies costs, e.g., Li-ion battery requires 2-6 replacements over a 30-year plant lifespan.[6] Compared to the conventional solar-driven absorption chillers, solar cooling with ATB offers more tangible advantages through simplified system architecture. By integrating energy storage directly into the working fluid (e.g., H_2O/LiBr), these systems eliminate the need for separate thermal storage units, reducing footprint requirements (particularly benefits space-constrained urban installations) and cutting manufacturing costs through component consolidation. Besides, the intrinsic dual-functionality (storage and cooling) avoids the efficiency penalties of intermediate heat transfer steps in conventional absorption systems.

Safety and stability. In addition, frequent reports of battery fires and explosions in recent years have raised growing concerns over the safety of large-scale battery storage systems in buildings.[7] These risks are further amplified by the current global instability, as buildings with extensive battery installations may become more vulnerable to external threats, thereby compromising both energy security and structural safety. In contrast, ATBs operate under vacuum conditions and pose no risk of fire or explosion.

Energy security and strategic reserves. Moreover, ATBs inherently contribute to energy security and resilience. Absorbent salts such as LiBr can be stockpiled in large quantities at relatively low maintenance cost and without significant degradation over long time. This feature enables ATBs to function not only as operational thermal storage devices but also as strategic reserves of thermal energy. In times of crisis or supply disruption, these reserves can provide a stable and secure alternative for sustaining essential cooling or heating demands, thereby enhancing the robustness of energy infrastructure.

Challenges

Despite its strong technical alignment with solar cooling applications, ATB faces several limitations and implementation challenges (Figure 1E).

First, the intermittent operation of ATBs—alternating between solar charging and cooling discharging—precludes continuous cooling output from a single unit, thereby limiting their applicability in scenarios requiring uninterrupted cooling. While technical solutions exist, such as deploying multiple complementary ATBs or integrating absorption chillers to enable continuous cooling, these approaches inevitably increase initial capital costs.

Furthermore, during the discharging process, the gradual dilution of the solution through vapor absorption leads to declining cooling capacity. Thus, there is a dynamic mismatch with user demand fluctuations driven by weather conditions and internal heat loads (e.g., equipment/personnel). To address this challenge, control strategies such as multi-level and variable-flow regulations[8] have been developed, mitigating output decay while improving load matching.

In addition, the working fluids in ATBs predominantly rely on lithium salt (particularly LiBr) solutions despite critical limitations of crystallization risk and increasing cost.[9] In closed systems, crystallization not only impairs performance through irreversible salt precipitation and pipe blockages but also risks equipment failure (e.g., pump damage), posing significant safety hazards. Compounding the technical challenges, LiBr prices have more than doubled over the past decade due to surging lithium demand, now accounting for >60%[10] of total system costs in ATB. Emerging alternatives, including crystallization-free ionic liquids and low-cost deep eutectic solvents,[10] represent promising pathways to enhance system reliability, operational flexibility, and economic viability, though heir high viscosity and long-term stability need to be further addressed and validated.

SUMMARY

Solar cooling presents a promising pathway for reducing carbon emissions in the building and transport sectors, yet widespread adoption is hindered by system complexity, high costs, and the mismatch between unstable solar energy and variable cooling demand. This study offers a brief analysis of existing solar conversion, energy storage, and cooling methods, with a particular focus on solar-driven ATB as an integrated solution. ATB combines energy storage and cooling functions in a single unit, offering ultra-high ESD and negligible standby thermal losses. By eliminating intermediate components and enabling low-temperature charging, ATB demonstrates strong potential for compact, scalable solar cooling from multiple perspectives. However, challenges such as intermittent operation, declining cooling capacity, and material constraints (especially the cost and crystallization risk of lithium salt) must be addressed. Future development on ATB should focus on working fluid development, system integration with renewable energy sources, and operation/control strategies for dynamic environments. This work identifies pathways to enhance ATB performance and reliability, providing strategic insights into their deployment in future decarbonized cooling systems.

REFERENCES

1. IEA. (2025). Solar thermal technologies deployed in around 400 million dwellings by 2030. *IEA.* DOI:https://www.iea.org/reports/solar-thermal-technologies-deployed-in-around-400-million-dwellings-by-2030.
2. Said Z., Pandey A., Tiwari A.K., et al. (2024). Nano-enhanced phase change materials: Fundamentals and applications. *Prog. Energy Combust. Sci.* 104:101162. DOI:10.1016/j.pecs.2024.101162
3. Ding Z., Wu W. and Leung M.K. (2022). On the rational development of advanced thermochemical thermal batteries for short-term and long-term energy storage. *Renew. Sustain. Energy Rev.* 164:112557. DOI:10.1016/j.rser.2022.112557
4. Ding Z., Sui Y., Zhai C., et al. (2023). Transient supply-demand matching and numerical parametric study of solar absorption thermal battery for space cooling. *Energy Conver. Manag.* 288:117177. DOI:10.1016/j.enconman.2023.117177
5. Ding Z., Sui Y., Lin H., et al. (2024). Experimental study on a two-stage absorption thermal battery with absorption-enhanced generation for high storage density and extremely low charging temperature (~50° C). *Appl. Energy* 363:123050. DOI:10.1016/j.apenergy.2024.123050
6. Mitali J., Dhinakaran S. and Mohamad A. (2022). Energy storage systems: A review. *Energy Stor. Sav.* 1:166–216. DOI:10.1016/j.enss.2022.07.002
7. Wang Q., Mao B., Stoliarov S.I., et al. (2019). A review of lithium ion battery failure mechanisms and fire prevention strategies. *Prog. Energy Combust. Sci.* 73:95–131. DOI:10.1016/j.pecs.2019.03.002
8. Ding Z. and Wu W. (2024). Simulation of a multi-level absorption thermal battery with variable solution flow rate for adjustable cooling capacity. *Energy* 301:131691. DOI:10.1016/j.energy.2024.131691
9. Sui Y., Lin H., Ding Z., et al. (2024). Compact, efficient, and affordable absorption Carnot battery for long-term renewable energy storage. *Appl. Energy* 357:122504. DOI:10.1016/j.apenergy.2023.122504
10. Sui Y., Ding Z., Zhai C., et al. (2023). Crystallization-free and low-cost deep eutectic solvents for absorption thermal battery utilizing ultra-low-grade energy. *Energy Conver. Manag.* 284:116984. DOI:10.1016/j.enconman.2023.116984

FUNDING AND ACKNOWLEDGMENTS

This work is supported by the National Natural Science Foundation of China (No. 52322812 and No. 52476019), the Shenzhen Science and Technology Program (JCYJ20230807114905012), and the Research Grants Council of Hong Kong (CityU 11218922).

DECLARATION OF INTERESTS

The authors declare no competing interests.