



Absorption Thermal Battery: A Rising Frontier for Efficient Thermal Utilization and Renewable Integration

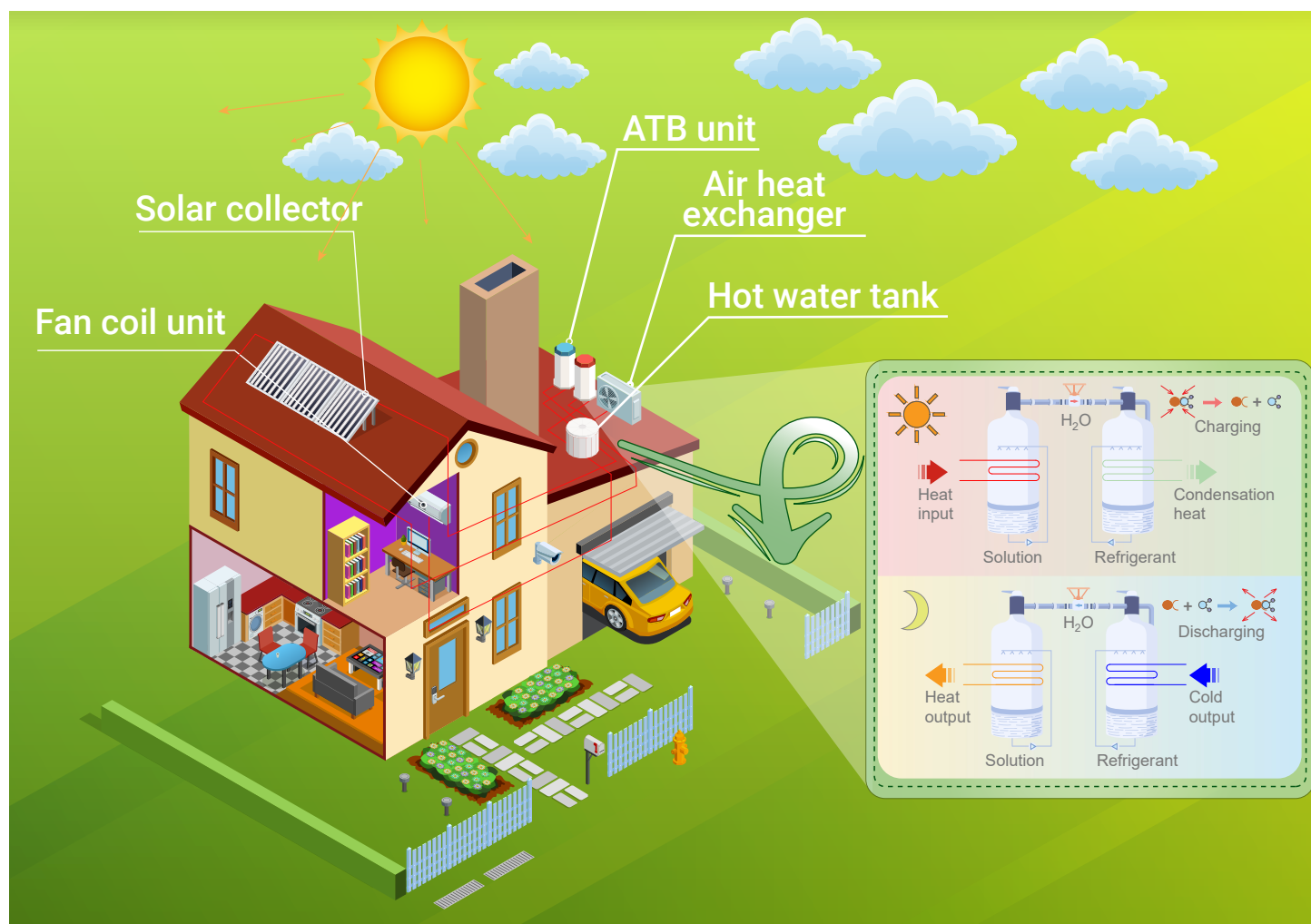
Zhixiong Ding,^{1,2,3} Yunren Sui,^{1,2,3} and Wei Wu^{1,2,*}

*Correspondence: Wei Wu Email: weiwu53@cityu.edu.hk

Received: August 22, 2025; Accepted: September 11, 2025; Published Online: September 25, 2025; <https://doi.org/10.59717/ipj.energy-use.2025.100002>

© 2025 The Author(s). This is an open access article under the CC BY license (<https://creativecommons.org/licenses/by/4.0/>).

GRAPHICAL ABSTRACT



PUBLIC SUMMARY

- Evolution of thermodynamic cycles enhancing energy storage density, efficiency, and adaptability.
- Development of novel absorbent-refrigerant pairs like ionic liquids and deep eutectic solvents.
- Experimental validation of ATB prototypes and integration into real-world applications for low-carbon energy.



INNOVATION
— PRESS —

Energy Use

Energy Use 1 (2025) 100002

Contents lists available at INNOVATION PRESS

Absorption Thermal Battery: A Rising Frontier for Efficient Thermal Utilization and Renewable Integration

Zhixiong Ding,^{1,2,3} Yunren Sui,^{1,2,3} and Wei Wu^{1,2,*}

¹School of Energy and Environment, City University of Hong Kong, Hong Kong SAR, China

²City University of Hong Kong Shenzhen Research Institute, Shenzhen 518057, China

³These authors contributed equally

*Correspondence: Wei Wu Email: weiwu53@cityu.edu.hk

Received: August 22, 2025; Accepted: September 11, 2025; Published Online: September 25, 2025; <https://doi.org/10.59717/ipj.energy-use.2025.100002>

© 2025 The Author(s). This is an open access article under the CC BY-NC-ND license (<https://creativecommons.org/licenses/by/4.0/>).

Citation: Ding Z., Sui Y. and Wu W. (2025). Absorption Thermal Battery: A Rising Frontier for Efficient Thermal Utilization and Renewable Integration. *Energy Use* 1:100002.

Absorption thermal batteries (ATBs) have emerged as a promising thermal energy storage technology capable of converting surplus low-grade heat into dispatchable heating and cooling outputs. By decoupling energy storage from temperature via concentration gradients, ATBs offer unique advantages over traditional sensible and latent heat storage systems, including low thermal losses, high energy storage density (ESD), and flexible output forms. This work provides a comprehensive overview of the recent progress in ATB research across three key dimensions. First, we examine the evolution of thermodynamic cycle designs—from basic configurations to advanced cycles—highlighting their impact on ESD, energy storage efficiency (ESE), and adaptability under varying thermal conditions. Also, some regulation strategies for stabilizing the discharging rate to improve the temporal flexibility and user-aligned performance of ATBs have been analyzed. Second, we explore the development of novel absorbent-refrigerant working pairs, focusing on emerging candidates such as ionic liquids (ILs) and deep eutectic solvents (DES), and discuss how data-driven molecular design approaches may accelerate breakthroughs in material discovery. Third, we review the experimental validation of ATB systems, summarizing the design, performance, and challenges of existing prototypes. Finally, we identify critical research directions for advancing ATBs toward real-world deployment: expanding experimental validation of advanced cycles, leveraging artificial intelligence for tailored working pair discovery, and integrating ATBs into application-driven contexts such as electronics and data center cooling, building HVAC, and cold-chain logistics. These efforts will be vital to realizing ATBs as a core solution for resilient and low-carbon thermal energy systems.

INTRODUCTION

As the global community accelerates its transition toward low-carbon energy systems,¹ thermal energy storage, also known as thermal battery, is emerging as a cornerstone technology to enable deeper integration of renewables.^{2,3} The growing reliance on variable solar and wind resources highlights a fundamental challenge: the mismatch between energy supply and end-use thermal demand, both in magnitude and timing.⁴ Unlike electrical storage, thermal battery directly addresses this mismatch in the thermal domain, where a significant share of final energy is consumed. By capturing excess heat or cold during periods of renewable surplus and releasing it on demand, thermal battery not only enhances system flexibility but also reduces reliance on fossil-based backup sources.⁵ Its ability to shift thermal loads across different time scales—from hours to seasons—makes thermal battery an essential component for decarbonizing heating and cooling

sectors, which together represent a major portion of global energy consumption and carbon emissions.⁶

Thermal battery technologies can be broadly categorized into three types based on their underlying mechanisms:⁷ sensible thermal battery (STB), latent thermal battery (LTB), and thermochemical thermal battery (TCTB), as shown in Figure 1A. Key performance indicators for thermal battery systems typically include energy storage density (ESD), energy storage efficiency (ESE), charging/discharging temperature, charging/discharging rate, and economic viability.⁸ STB is the most established and straightforward method for thermal storage, relying on the temperature change of a storage medium,⁹ such as water, oil, rocks, or salts, which are inexpensive and widely available. However, the limited temperature difference imposed by the heat source and demand constrains the ESD of STB systems. Moreover, large temperature gradients between the system and ambient lead to significant heat losses, necessitating effective insulation.¹⁰

LTB systems store and release thermal energy through the phase change of the storage materials, offering higher ESD and stable operating temperatures during charge and discharge.¹¹ These advantages have spurred extensive research interest over the past decades.^{12–14} Nonetheless, challenges such as low thermal conductivity, supercooling, and phase segregation have hindered their large-scale deployment.¹⁵

TCTB includes chemical reaction-based and sorption-based systems.¹⁶ While chemical reaction-based systems offer high ESD, they generally require elevated temperatures or pressures, making them unsuitable for low-grade heat utilization.¹⁷ Sorption-based thermal batteries can be further divided into adsorption-based and absorption-based systems.¹⁸ Adsorption-based storage systems are compact and charge at relatively low temperatures, but their performance is limited by poor heat transfer in solid sorbents.^{19,20} In contrast, absorption-based storage, also known as absorption thermal battery (ATB), offers a compelling balance in high ESD, low charging temperature, and system flexibility.^{21–23} The use of liquid working pairs enhances both heat and mass transfer, enabling faster charging/discharging rates.²⁴ Importantly, by converting thermal energy into concentration gradients, ATB can minimize thermal losses during long-term storage, outperforming both STB and LTB in storage efficiency.^{25,26} Furthermore, it allows versatile energy output,²⁷ including cooling, heating, and dehumidification,²⁸ driven by low-grade heat sources.²⁹ Therefore, solar thermal collectors,³⁰ wind-generated heat,³¹ industrial waste heat,³² etc., can potentially be used to drive ATB. As shown in Figure 1B, ATB systems (e.g., H₂O/LiCl, H₂O/LiBr) exhibit superior ESD compared to other thermal battery technologies when operating below 200 °C, reinforcing their potential for future low-carbon energy applications.

As illustrated in Figure 1C, a typical ATB comprises a solution tank, a

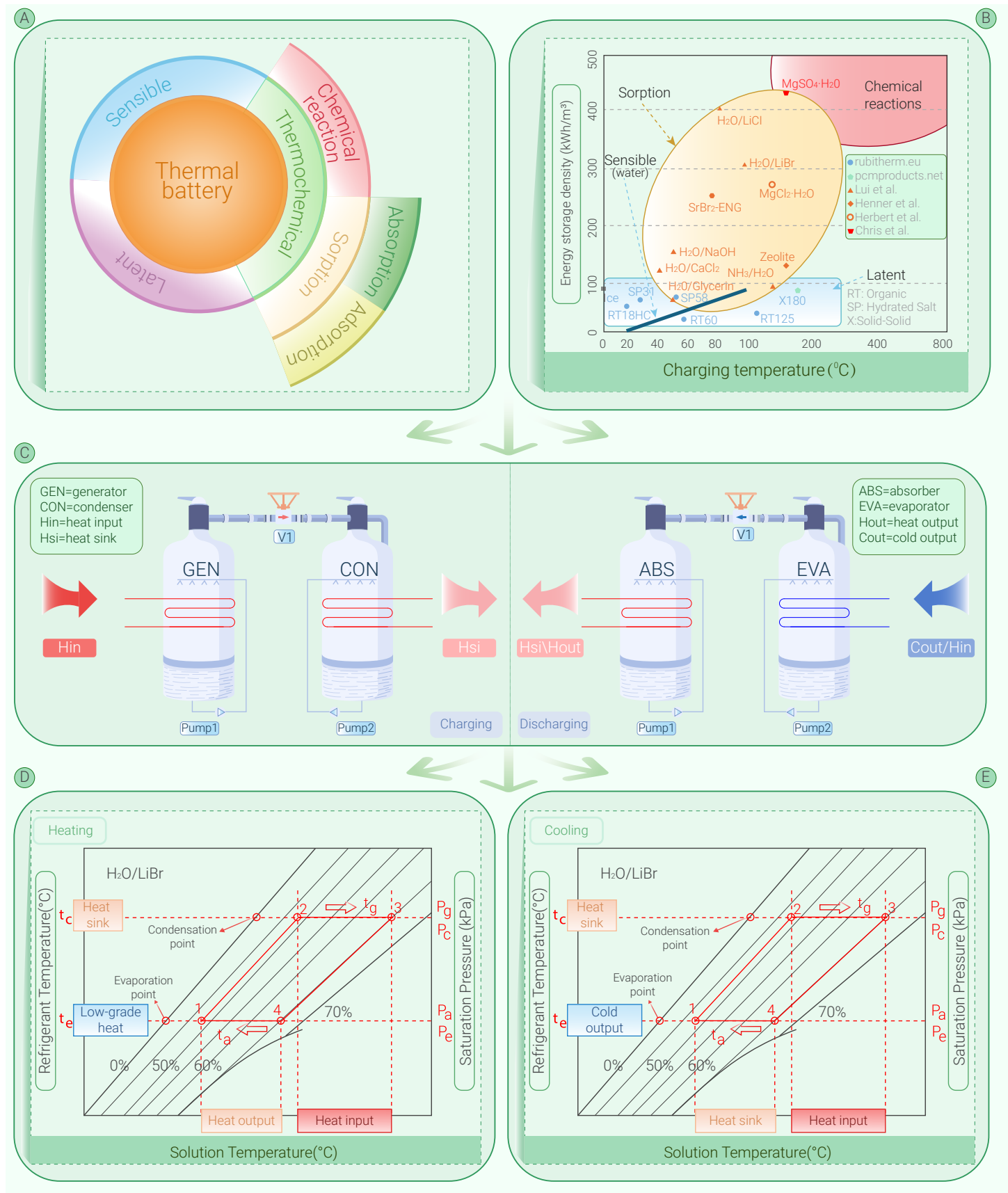


Figure 1. (A) Classification of thermal batteries, (B) comparison of ESD and charging temperatures between various thermal batteries,^{34, 35, 36, 37, 38, 39} (C) a typical configuration of ATB system, (D) working flow of cooling mode on PTX diagram, (E) working flow of heating mode on PTX diagram.

refrigerant tank, a vapor pipe connecting the two tanks, and a valve installed on the pipe for on-off control. Each tank is equipped with a heat exchanger to serve as channels for thermal energy input and output. Spray heat exchange-

ers are the most commonly used for their excellent heat and mass transfer.³³ During the charging process, the solution tank functions as a generator, connected to an external heat source, typically low-grade heat such as solar

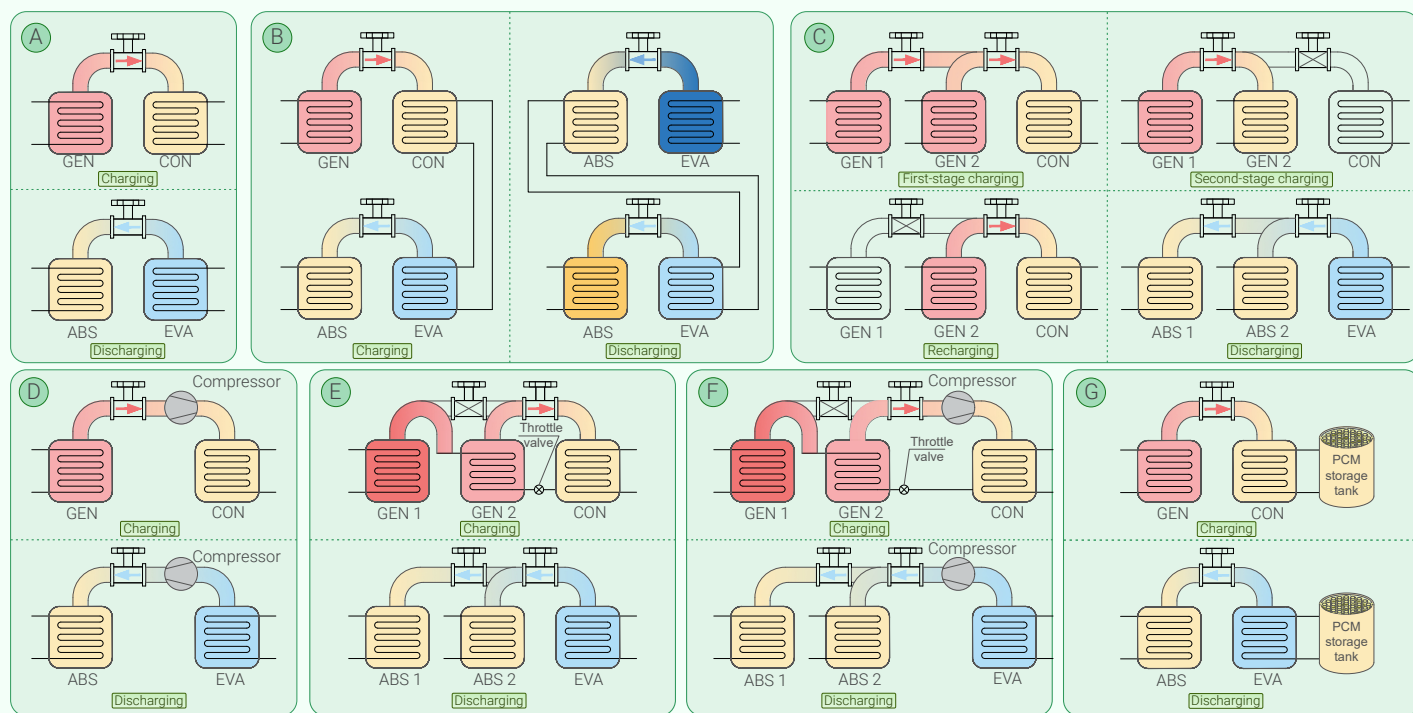


Figure 2. Advanced/hybrid ATB cycles. (A) basic cycle, (B) double-stage cycle, (C) two-stage cycle, (D) compression-assisted cycle, (E) double-effect cycle, (F) double-effect compression-assisted cycle, (G) PCM-assisted cycle.

energy or industrial waste heat in the range of 70–90 °C. The refrigerant tank acts as a condenser, rejecting heat to an external heat sink. The input heat drives desorption in the generator, producing refrigerant vapor, which travels through the vapor pipe and condenses in the refrigerant tank, releasing condensation heat. As desorption proceeds, the solution becomes increasingly concentrated (i.e., from point 2 to point 3, as shown in Figure 1 D & E), effectively storing thermal energy in the form of a concentration gradient. Once charging is complete, the valve is closed to prevent vapor backflow and preserve the stored potential. When heating or cooling is required, the system transitions to the discharging mode by opening the valve. The concentrated solution absorbs refrigerant vapor to ensure continuous evaporation in the refrigerant tank. In heating applications (Figure 1D), the solution tank serves as an absorber delivering useful heat, while the refrigerant tank acts as an evaporator extracting ambient heat. In cooling scenarios (Figure 1E), the absorber is linked to an external heat sink to reject the absorption heat, while the evaporator provides cooling directly to the conditioned space.

As an emerging thermal battery technology, ATB has seen notable progress in recent years.⁴⁰ However, its potential remains underexplored, and a comprehensive review of ATB is still lacking. This work addresses that gap by systematically reviewing the state-of-the-art in ATB research from three perspectives: the establishment of advanced/hybrid cycles, the discovery of novel absorbent-

refrigerant working pairs, and the development of experimental prototypes. By integrating insights from these dimensions, the review outlines the current technological landscape of ATBs, identifies key challenges hindering their deployment, and explores promising application scenarios where ATBs could offer unique advantages in harnessing low-grade thermal energy and enabling flexible energy use.

ADVANCED ATB CYCLES

The charging process of ATB relies on a temperature difference to drive the desorption of refrigerant from the solution. This requires both a heat source to heat the solution and a heat sink to condense the generated refrigerant vapor. In most practical implementations, the heat sink temperature is close to the ambient temperature since it is usually a natural cold source, e.g., air or water, which typically ranges from 20 °C to 35 °C. Under such heat sink conditions, a basic ATB cycle generally requires a heat source temperature of

70–90 °C⁴⁰ to achieve sufficient desorption and realize an effective charging process. However, when the available heat source falls below this range, the driving potential for desorption is diminished. As a result, the solution cannot be concentrated to a sufficiently high level, which directly limits the ESD. A reduced ESD not only constrains the amount of thermal energy that can be stored but also shortens the discharge duration and lowers the discharging rate and capacity, ultimately degrading the overall performance and applicability of the ATB system. Specifically, the low solution concentration at the end of the charging process is insufficient to support demanding discharge conditions, e.g., cooling under high-temperature environments or heating under low-temperature conditions.⁴¹ Addressing this temperature sensitivity is therefore critical for expanding the use of ATBs with low-grade and variable heat sources, such as solar thermal and industrial waste heat.

To overcome this limitation, Xu et al.⁴² proposed a four-tank double-stage ATB cycle (Figure 2B) and systematically investigated its performance under varying operating conditions for both heating and cooling applications. The double-stage ATB architecture consists of two coupled basic ATB sub-cycles. During the charging phase, the auxiliary sub-cycle operates in discharging mode to provide cooling for the main storage cycle. By utilizing the evaporative cooling from the auxiliary cycle as the condensation sink, the effective condensation temperature of the main storage cycle is significantly reduced, which enables the main storage cycle to charge at lower heat source temperatures. This coupling enables higher charging concentrations and then strengthens the discharging process of the main storage cycle. Therefore, the results indicated that under an ambient condition of 30 °C and a chilled water temperature of -5 °C, the ESD of the double-stage cycle increased by 138% relative to the basic cycle, albeit with a 20% reduction in ESE. Notably, under extreme cold ambient (-10 °C), where the basic cycle fails to operate, the double-stage cycle still delivered 40 °C heating output with an ESD of 293.9 kJ/kg and an ESE of 0.18.

In a parallel study of double-stage discharging,⁴³ a heating auxiliary sub-cycle is integrated to support evaporation of the main sub-cycle, thereby enhancing the absorption process to deliver high heating temperature and enabling lower discharging concentrations (Figure 2B). At an ambient temperature of 5 °C and a target hot water temperature of 50 °C, this configuration achieved an ESD of 254.0 kJ/kg (equivalent to 110.0 kWh/m³), which is a 7.32-fold increase over the basic cycle.

To further improve system compactness, Ding et al.⁴⁴ proposed a three-tank two-stage ATB cycle (Figure 2C). In contrast to the four-tank double-stage cycle, this configuration eliminates one tank by directly connecting the auxiliary and main solution tanks during the charging process. The absorption effect in the auxiliary tank is harnessed to enhance desorption in the main tank, thereby increasing the ending concentration. Experimental prototype demonstrated that, under a heat source temperature of 70 °C, the two-stage cycle increased the ESD from 62.7 kWh/m³ (163.1 kJ/kg) to 100.0 kWh/m³ (260.1 kJ/kg), while the ESE showed a slight decrease from 0.53 to 0.46. Notably, the two-stage prototype remained operational at charging temperatures as low as 50 °C, significantly expanding the charging temperature range to include a wide scope of low-grade renewable and waste heat sources. Their further work investigated solution charge distribution strategies between the two solution tanks in the two-stage ATB cycle,⁴⁵ revealing that a higher proportion of solution should be allocated to the main tank at high charging temperatures to maintain performance. Moreover, they pointed out that the two-stage cycle is particularly well-suited for long-term thermal storage, including seasonal and hybrid storage modes, such as storing cold in winter for summer cooling, or storing heat in summer for winter heating.

In addition to thermodynamic cycle optimization, compression-absorption hybrid system configuration (Figure 2D) has also been explored to enhance the storage performance for ATB systems, particularly in reducing the charging temperature and increasing ESD.⁴⁶ Under a heat source temperature of 80 °C, the basic ATB cycle exhibited an ESD of 104.8 kWh/m³ and an ESE of 0.58. The compression-assisted modes led to marked improvements: charging compression increased the ESD to 143.1 kWh/m³ and ESE to 0.62; discharging compression yielded an ESD of 245.7 kWh/m³ and ESE of 0.70; and combined charging-discharging compression further boosted ESD to 282.8 kWh/m³ with a corresponding ESE of 0.67.⁴⁷

When there are favorable heat sources, e.g., exceeding 150 °C, the basic ATB cycle can readily achieve high solution concentrations in the charging process. However, in such high-temperature regimes, the basic ATB cycle often fails to capitalize on the full potential of the heat source. Instead of improving system performance, the ESE may stagnate or even decline due to increased sensible heat losses during charging. To address this inefficiency, Ding et al.⁴⁸ proposed a double-effect ATB cycle that introduces a low-temperature solution tank to recover the condensation heat from the high-temperature solution tank for secondary desorption (Figure 2E). The cascading utilization of the thermal input enables more effective use of high-temperature heat sources. Results demonstrated that the double-effect cycle significantly enhanced the ESE. In both cooling and heating modes, the ESE exceeded 1.0, indicating that the thermal energy output surpassed the direct thermal input. When operating within a charging temperature range of 160–200 °C, the cooling-mode ESE was improved by 57.1% to 61.6%, reaching a peak of 1.27. In heating mode, the ESE gains ranged from 58.2% to 61.8%, with a maximum value of 1.44.

To extend the applicability of double-effect ATB to lower-grade heat sources, Ding et al.⁴⁹ further proposed a double-effect compression-assisted ATB cycle (Figure 2F). At a charging temperature of 130 °C, the double-effect compression-assisted cycle demonstrated a 24% increase in ESE and a 145% enhancement in ESD compared to the double-effect baseline. The optimal charging temperature range for the enhanced cycle was found to be 100–150 °C, effectively bridging the gap between conventional single-effect and double-effect cycles. This advancement not only improves the utilization of medium-temperature thermal resources, such as concentrated solar or industrial waste heat, but also enhances the flexibility and adaptability of ATB systems across diverse application scenarios.

While low ambient temperatures are generally favorable for condensation during the charging process of the ATB cycle, they can significantly impair heat output during the discharging process by limiting the evaporation to extract sufficient low-grade thermal energy from the environment. To address this challenge, Ding et al.⁴¹ proposed a phase change material (PCM)-assisted ATB cycle (Figure 2G), in which the condensation heat is captured and stored during charging in a PCM storage tank. Although the recovery of condensation heat slightly weakens the charging process, the system can switch back to natural cooling once the PCM reaches full charge, thereby preserving the final solution concentration. During discharge, if the ambient

heat is insufficient to sustain evaporation, the stored heat in the PCM tank can be released to heat the evaporator, enhancing refrigerant vapor evaporation, and strengthening the absorption process, ultimately improving heating capacity. Both paraffin and salt-based PCMs demonstrated notable performance improvements. The ESE increased from 0.73 to 0.76 with paraffin and to 0.78 with salt; meanwhile, the ESD was enhanced by 64% and 100%, respectively. These results highlight the value of PCM-assisted thermal buffering in mitigating environmental constraints and expanding the operational envelope of ATB systems in cold climates.

Beyond the timing mismatch between energy supply and demand, a more fundamental challenge in thermal energy utilization lies in the grade (i.e., temperature) gap,⁵⁰ which cannot be bridged by the existing STB and LTB. ATB stores energy by converting input heat into a chemical potential difference, i.e., a concentration gradient. Upon discharge, the concentration gradient drives the absorption of refrigerant vapor, converting chemical potential back into a temperature difference and enabling heat release. If additional thermal energy is supplied to the evaporator during discharge, the absorber can deliver heat at a temperature higher than that of the heat source, effectively upgrading the energy grade⁵¹ (Figure 3A & B). Analogous to the nomenclature of absorption heat pumps, such systems may be referred to as type II ATB or absorption energy storage heat transformer (ESHT).

Unlike conventional ATB cycle, ESHT involves direct heating of the evaporator by an external thermal source in the discharging process. This additional heat input elevates the internal system pressure (Figure 3C), thereby the absorber operates at a higher equilibrium temperature, enabling the delivery of thermal output at significantly increased temperatures compared to the conventional ATB. While the ESHT cycles exhibit ESD comparable to conventional ATBs, their ESE is reduced due to the auxiliary heat input to the evaporator during discharge. Nevertheless, the ability to deliver higher-temperature heat improves the exergy efficiency (EXE), offering distinct advantages for low-grade heat sources and high-temperature applications. For instance, under input and output temperatures of 60 °C and 90 °C, respectively, a temperature lift of 30 °C was achieved with an ESD of 137.5 kWh/m³, an ESE of 0.37, and an EXE of 0.49.⁵¹ Parametric analyses further indicate a trade-off between heat upgrading ability and storage performance, underscoring the need for application-specific optimization in system design.

To enhance both thermal output and performance, a hybrid compression strategy has been introduced into ESHT,⁵² as shown in Figure 3D. The application of the compressor increased the ESD from 35.2 to 282.7 kWh/m³, the ESE from 0.24 to 0.43, and the EXE from 0.32 to 0.54. The maximum temperature lift was improved from 30 °C to 65 °C. Then, the double-stage strategy has been adapted to these systems (Figure 3E), wherein the absorption heat from an auxiliary sub-cycle is used to preheat the main sub-cycle evaporator, further increasing discharge temperature and improving the effective thermal upgrading capacity.^{53,54} The two-stage ESHT has also been investigated (Figure 3F) with the maximum temperature lift increased from 30 °C to 50 °C, and the minimum charging temperature of 55 °C.⁵⁵

Although the advanced/hybrid ATB cycles have significantly improved both the energy storage performance and thermal output quality, a critical bottleneck remains: the decline in thermal output rate during the discharging process due to dilution of solution. The attenuated output cannot sustain consistent thermal delivery and continues to hinder the practical deployment of ATBs in real-world applications.^{59,60}

To address the discharge degradation problem, Xu et al.²⁴ proposed a once-through discharging strategy that structurally separates the solution tank into two tanks: one for concentrated solution and one for dilute solution. During the charging process, a dilute solution is extracted from its tank and regenerated and then stored in the concentrated tank. During the discharging process, the concentrated solution is drawn from its tank and directed into the dilute tank, where absorption occurs. This once-through configuration ensures that the solution concentration entering the heat exchanger remains constant throughout the discharge period. As a result, the system maintains a stable temperature output, effectively decoupling thermal performance from concentration depletion and enhancing the reliability and controllability of the ATB under dynamic operating conditions. Moreover, Ding et al.⁶¹ proposed a multi-level regulation strategy that stabilizes thermal output in multiple and switchable levels (Figure 4A). The approach involves integrating

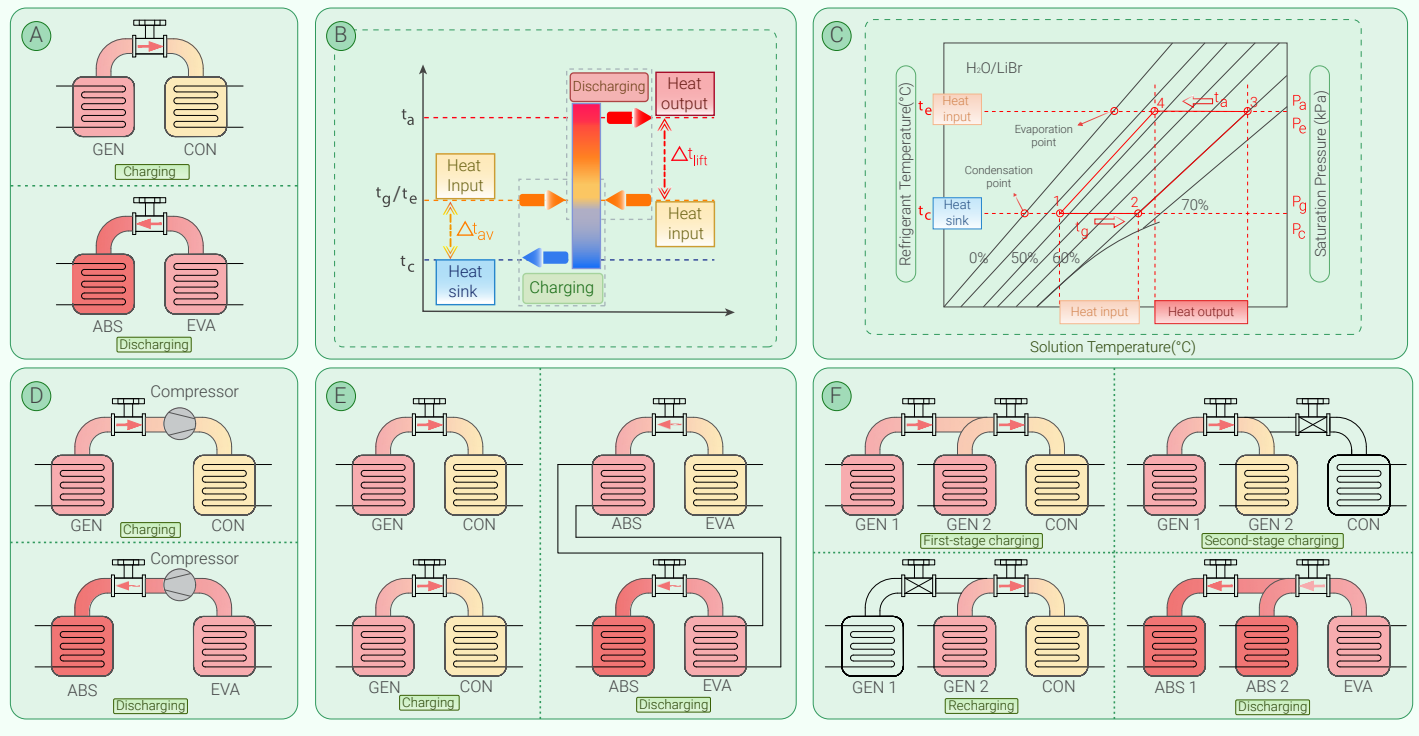


Figure 3. Type II ATB (ESHT) cycles for temperature upgrading. (A) basic ESHT, (B) working principle of ESHT, (C) working flow of ESHT on PTX diagram, (D) compression-assisted ESHT, (E) double-stage ESHT, (F) two-stage ESHT.

Table 1. Performance summary of advanced/hybrid ATB cycles⁵⁶

Items	Working pairs	Operation temperature		Storage performance		Reference
		T _{in} /°C	T _{out} /°C	ESE	ESD	
Double-stage ATB	NH ₃ /H ₂ O	90	40	0.18	293.9a	[42]
		90	-5	0.27 (0.34)	123.2b (89.3b)	
		90	50	0.4 (0.18)	254.0a (34.7a)	
	H ₂ O/LiBr	85	11	0.44	110.0b (17.0b)	[43]
		85	13	0.43	143a	
		85	50	0.38 (0.46)	175a	
Compression-assisted ATB	H ₂ O/LiBr	80	7	0.67 (0.58)	257a (130a)	[57]
Two-stage ATB	H ₂ O/LiBr	70	3.5-10.9	0.46 (0.53)	282.8b (104.8b)	[58]
Double-effect ATB	H ₂ O/LiBr	160	40	0.46 (0.53)	260.1a (163.1a)	[44]
		160	7	1.44 (0.89)	100b (62.7b)	
		160	7	95.9b (98.6b)	84.2b (86.9b)	
Double-effect compression-assisted ATB	H ₂ O/LiBr	130	7	1.27 (0.79)	84.2b (86.9b)	[49]
PCM-assisted ATB ESHT	H ₂ O/LiBr	80	45	1.24(1.00)	231.9b (94.6b)	[41]
Compression-assisted ESHT	H ₂ O/LiBr	80	45	0.78 (0.73)	141.5b (70.7b)	[51]
Double-stage ESHT	H ₂ O/LiBr	80	110	0.37	137.5b	[52]
	H ₂ O/LiBr	60	90	0.43 (0.24)	282.7b (35.2b)	[53]
	H ₂ O/LiBr	65	95	0.19	54.8b	[54]

Note: The values in () represent the performance of the corresponding basic cycle. The superscript "a" indicates units of kJ/kg, while "b" indicates units of kWh/m³.

multiple solution tanks, each storing solution at distinct concentrations. By actively switching the inlet concentration to the absorber during discharge, the system maintains a steady output across several levels, effectively transforming the inherently decaying thermal release process into a staircase-like profile. Analogous to the "high- medium-low" control scheme in conventional air-conditioning systems, this method allows users to select output modes based on real-time cooling or heating demand, thereby enhancing system flexibility and operational responsiveness.

Beyond gradual output decline, Ding et al.⁶² further recognized that demand-supply mismatch may also manifest as excessive initial output due to high concentration at the beginning of discharge. To mitigate this, a vari-

able-flowrate regulation strategy was proposed (Figure 4B), wherein solution flowrate or heat transfer fluid flowrate is adaptively controlled to modulate output in real time.

Specifically, lower flowrates are applied in the early stages of discharge to avoid output overshoot, while higher flowrates in the latter stages compensate for weakened concentration gradients. By integrating variable-frequency pumps and feedback controls, this strategy achieved over 12 hours of stable thermal output. Then, a year-round dynamic simulation model of solar-driven ATB for cooling was developed and applied to four representative cities, i.e., Beijing, Shanghai, Hong Kong, and Singapore, spanning a wide range of latitudes and climate zones.⁶³ The results demonstrated a high annual cooling

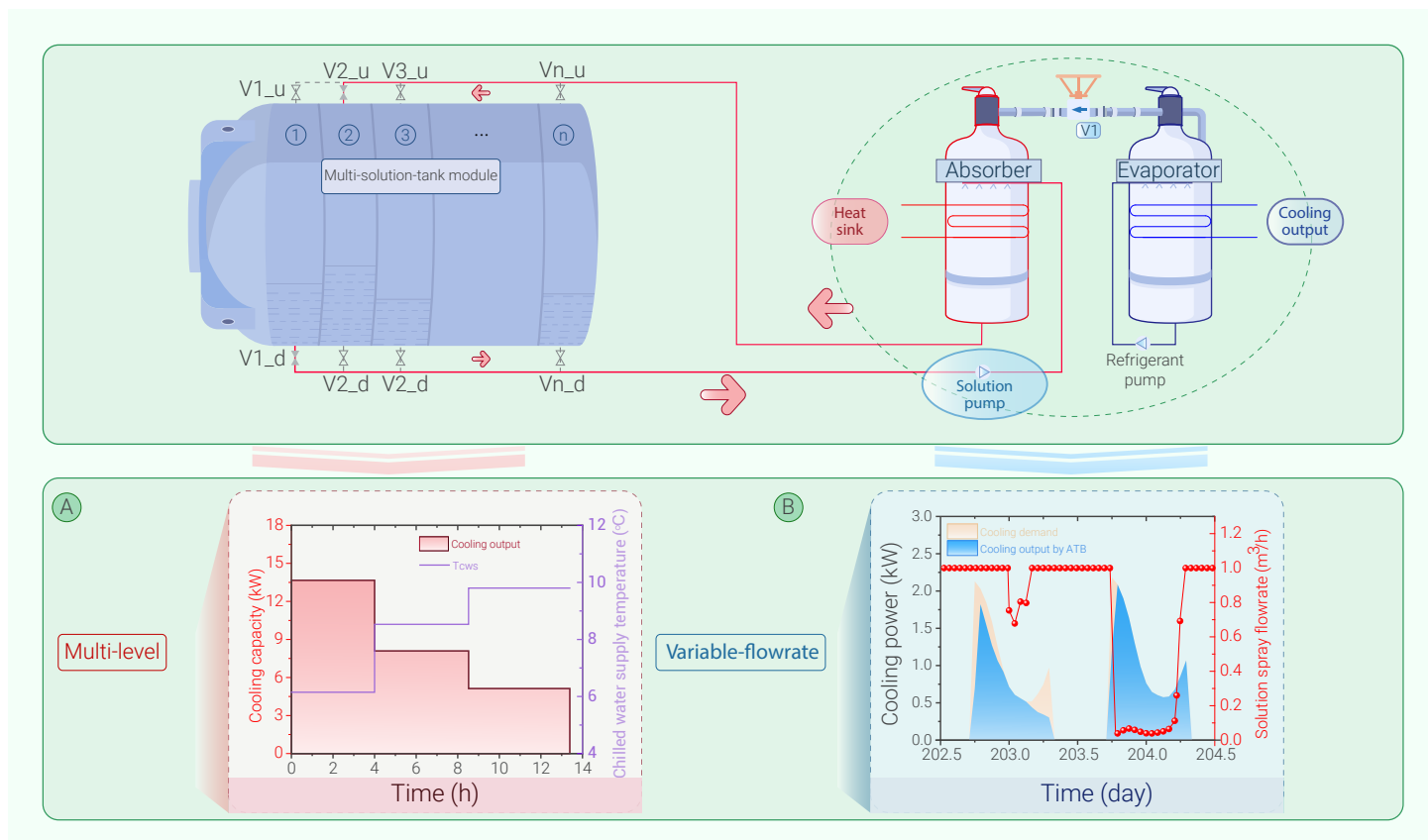


Figure 4. Discharging regulation strategies. (A) multi-level regulation, (B) variable-flowrate regulation.

met ratio across all locations, with the highest value of 94%.

NOVEL ATB WORKING FLUIDS

Working fluids, referred to as the "blood" of absorption thermal batteries, play a crucial role in determining both the dynamic behavior and energy storage performance. $\text{H}_2\text{O}/\text{hygroscopic salts}$ (e.g., $\text{H}_2\text{O}/\text{LiBr}$) are among the most widely used due to their high ESE, and have been extensively applied in absorption heat pumps and ATB cycles.⁶⁴ However, $\text{H}_2\text{O}/\text{LiBr}$ systems are prone to crystallization under high heat source temperatures and low heat sink temperatures, which poses

significant challenges to system reliability. Alternatively, $\text{NH}_3/\text{H}_2\text{O}$ exhibits favorable cycle performance at lower temperatures and is therefore commonly employed in ice-making and low-temperature refrigeration applications.⁵⁵ Nevertheless, $\text{NH}_3/\text{H}_2\text{O}$ systems typically require rectifiers to purify the refrigerant vapor, thereby increasing system complexity and cost.⁶⁶ To address this issue, NH_3/salts have been investigated as rectifier-free alternatives with improved cycle performance,⁶⁷ though they still suffer from crystallization risks,^{68,69} which hinders their broader application in absorption cycles.

In recent years, ionic liquids (ILs) have emerged as promising materials for absorption technologies, with the potential to overcome some intrinsic limitations of salt-based working fluids. IL-based working fluids possess crystallization-free nature and wide applicable temperature ranges, making them attractive candidates for ATBs.^{70,71} Unlike traditional hygroscopic salts, ILs consist of organic cations and large anions,⁷² whose asymmetric structures weaken the ionic interactions and lower the melting point, enabling ILs to remain liquid at room temperatures and thus mitigating the crystallization issue common in traditional fluids.⁷³ The structural tunability of ILs allows for customizable physicochemical properties through the selection and modification of cations and anions.⁷⁴ Figure 5A & B presents representative structures of common cations and anions in ILs, which illustrate their chemical composition and characteristics.⁷²

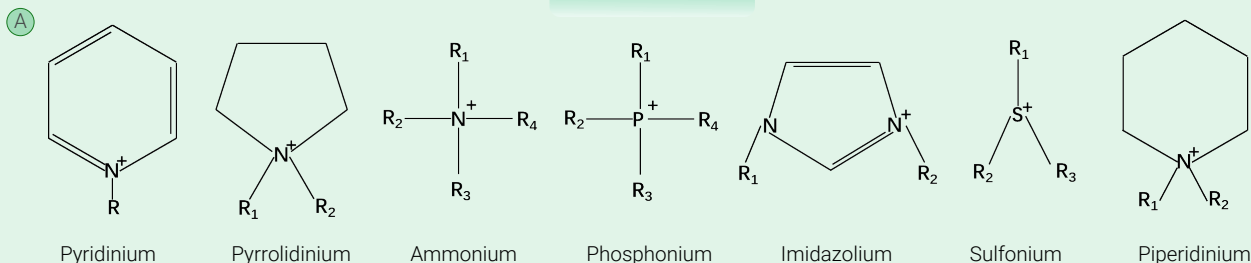
In 2006, Sen et al.⁷⁵ first proposed the application of ILs as absorbents in absorption refrigeration cycles, highlighting their non-volatile, non-toxic, and non-flammable nature. To enhance the energy conversion efficiencies of

absorption cycles, IL-based working fluids should exhibit high heat and mass transfer coefficients. Yokozeki et al.^{76,77} experimentally measured the solubility of ammonia and water in various ILs such as $[\text{EMIM}][\text{OAc}]$, and combined pressure-temperature-concentration (PTX) data with equation-of-state (EOS) modeling to reveal the potential of NH_3/ILs and $\text{H}_2\text{O}/\text{ILs}$ in absorption cycles. Zhang et al.⁷⁸ conducted simulation studies to assess the thermodynamic performance of $\text{H}_2\text{O}/[\text{EMIM}][\text{DMP}]$ in absorption cycles. The results showed that although the energy conversion efficiency was slightly lower than that of conventional $\text{H}_2\text{O}/\text{LiBr}$, it remained above 0.7 with a lower driving temperature, making it suitable for low-temperature heat source conditions.

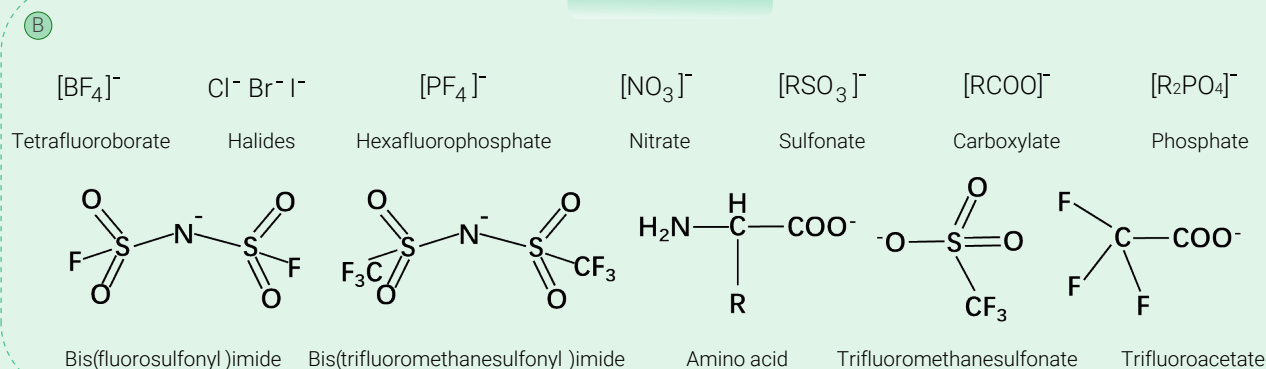
In addition, Boman et al.⁸⁰ performed a comprehensive analysis of the thermophysical properties and cycle performance of novel working fluids, demonstrating that water-based pairs offer the highest efficiency for cooling applications. Gao et al.⁸¹ developed a prediction model (Figure 6B) correlating the thermophysical properties of IL-based working fluids with their cycle performance, identifying affinity between absorbent and refrigerant and the excess enthalpy of absorption as key parameters. This model provides valuable guidance for the design and screening of working fluids in ATB cycles. The screening results showed that $[\text{EMIM}][\text{EtSO}_4]$ exhibited the highest ESE (0.62) and EXE (0.32).⁸² Wu et al.^{82,83} applied $\text{H}_2\text{O}/\text{ILs}$ in ATB cycles to achieve crystallization-free operation and improved performance: they developed dynamic ATB models considering fluid properties for various $\text{H}_2\text{O}/\text{ILs}$, compared the cycle performance of 14 IL-based working fluids, and found that $\text{H}_2\text{O}/[\text{DMIM}][\text{DMP}]$ yielded the highest ESE (0.745), while $\text{H}_2\text{O}/[\text{EMIM}][\text{OAc}]$ achieved the highest ESD (87.5 kWh/m^3).⁸⁴ $\text{H}_2\text{O}/[\text{EMIM}][\text{EtSO}_4]$ was identified as optimal for compression-assisted ATBs under low-temperature driving heat source temperature. Given the wide molecular diversity and tunability of ILs, data-driven machine learning models facilitate high-accuracy predictions and high-throughput molecular screening,^{85,86} revealing the significant potential of ILs in enhancing the cycle performance of absorption technologies.

However, the high cost and complex synthesis of ILs still limit their economic viability for large-scale deployment.⁸⁷ Therefore, reducing the cost and simplifying the synthesis of novel working fluid pairs remains a key

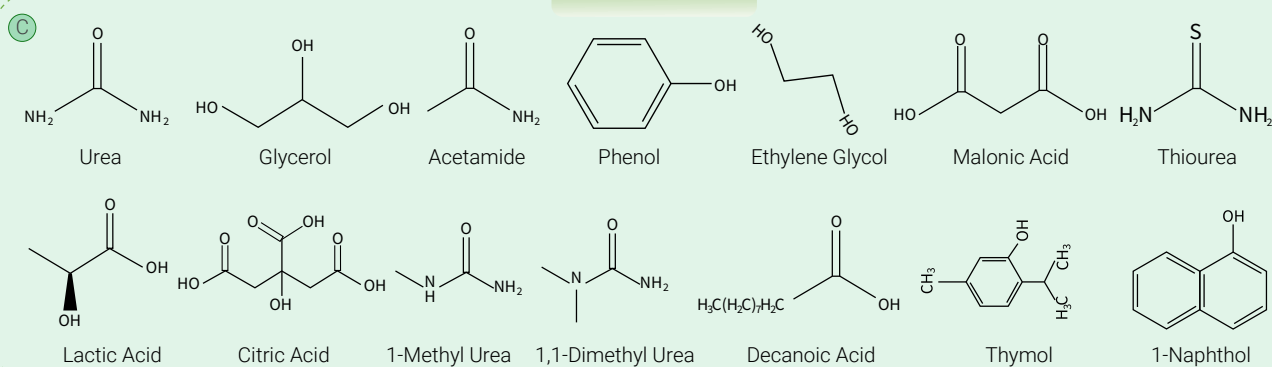
Cations



Anions



HBDs



HBAs

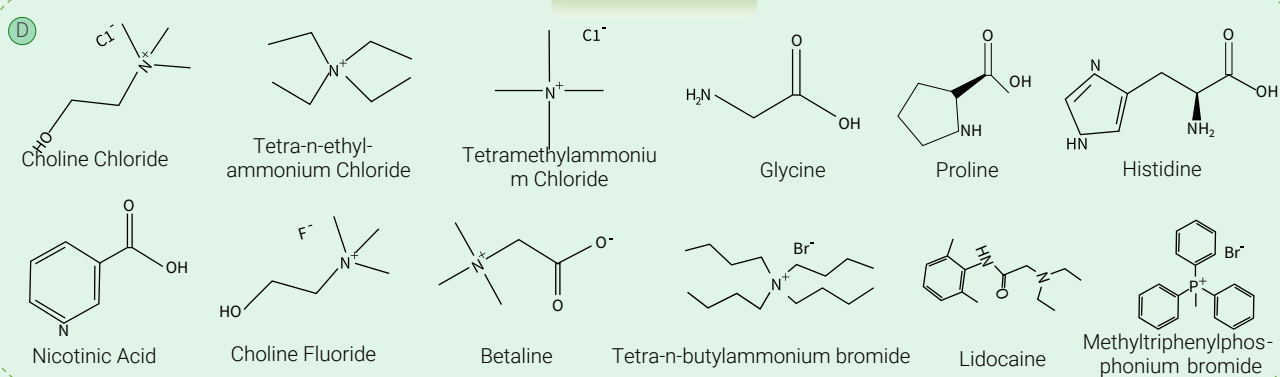


Figure 5. Potential working fluids for absorption thermal batteries. (A) molecular structures of common cations in ILs,⁷² (B) molecular structures of common anions in ILs,⁷² (C) molecular structures of common hydrogen bond donors in DESs,⁷³ (D) molecular structures of common hydrogen bond acceptors in DESs.⁷³

research priority for the future development of the ATB cycles. Deep eutectic solvents (DESs), which share similar thermophysical characteristics with ILs, have gained increasing attention as a new class of green absorbents for absorption cycles due to their crystallization-free nature, biodegradability, and low-cost preparation.⁸⁸⁻⁹⁰ DESs are mixtures formed by hydrogen bond acceptors (HBAs) and hydrogen bond donors (HBDs), and their eutectic structure leads to significantly reduced melting points.⁹¹ As research progresses, the diversity of DESs has expanded. Figure 5C & D illustrates typical structures of HBAs and HBDs. It is estimated that combinations of these constituents can yield approximately 106-108 distinct binary DES mixtures.

Abedin et al.^{92, 93} used molecular dynamics simulations to study the interactions between refrigerants and DESs, exploring their applicability in absorption refrigeration. Haghighbakhsh et al.^{94, 95} theoretically assessed the use of DESs in absorption cycles and compared their performance with salt- and IL-based working fluids, concluding that DES-based working fluids demonstrate superior energy efficiency. Nessakh et al.⁹⁶ evaluated the performance of two H₂O/DES in absorption heat transformers and achieved significant temperature lift, supporting the feasibility of DESs in absorption technologies.

To further assess the techno-economic potential of ATB technologies, Sui et al.⁶⁹ compared the energy storage performance of five H₂O/DESs, four NH₃/DESs, and three salt-based working fluids in both basic and compression-assisted ATBs. H₂O/Ethylene achieved the highest ESE and ESD among water-based working fluids; NH₃/Glycine exhibited the best performance with ESE and ESD reaching 0.736 and 452.98 kJ/kg among ammonia-based working fluids. The leveled cost of storage (LCOS) of different ATB cycles and working fluids is investigated and compared in Figure 6C. Due to the low cost and biodegradability of DESs, the leveled cost of ATBs using H₂O/DESs can be reduced by up to 41.9% compared to conventional H₂O/LiBr (Figure 6D). To achieve cost-effective long-term energy storage, a novel multi-cell ATB cycle using DESs⁹⁷ is applied to store the solar energy during winter and produce a cooling effect during summer (Figure 6E). Compared to sensible and latent thermal energy storage, DES-based ATB demonstrates superior ESD and a competitive leveled cost of storage (0.032-0.040 USD/kWh), positioning it as a promising solution for cost-effective and large-scale seasonal thermal energy storage technologies. Therefore, DESs eliminate crystallization risks and significantly reduce the leveled cost of storage, offering great promise for next-generation thermal energy storage technologies.

In summary, recent advancements in novel working fluid development have positioned ILs and DESs as promising candidates for next-generation ATB cycles. ILs offer crystallization-free operation and tunable molecular structures, enabling enhanced energy storage performance, though their high cost and synthesis complexity remain barriers to large-scale deployment. In contrast, DESs combine similar thermophysical advantages with low cost and biodegradability, demonstrating high ESE and a competitive leveled cost of storage. With support from data-driven models and system-level optimization, IL- and DES-based ATBs are poised to enable high-density, stable, and cost-effective absorption thermal energy storage.

EXPERIMENTAL PROTOTYPES OF ATB

Prototype development represents a critical bridge between conceptual innovation and real-world application for emerging technologies. In the case of ATB, which operates as closed, high-vacuum systems, the transition from theoretical frameworks to functional prototypes poses significant engineering challenges. As a result, reported ATB demonstrators remain scarce, and experimental validation is still in its early stages.

Weber et al.⁹⁸ developed a laboratory-scale ATB prototype utilizing the H₂O/NaOH working pair (Figure 7A). The system was equipped with 200 L solution and refrigerant tanks, both constructed from stainless steel (AISI 316) to ensure corrosion resistance. The study provided operational insights into the charging process, including low-pressure-technology-related issues, control methods, and some operational experience. However, the authors noted that the discharge phase remained underexplored, and no data on dynamic system behavior were reported. Similarly, N'tsoukpoe et al.⁹⁹ constructed an 8 kWh prototype based on the H₂O/LiBr working pair, designed to deliver 1 kW of thermal output (Figure 7B). Stainless steel was

used for the pipes, reactor, and water tanks, while the solution tank was made of transparent glass to facilitate visual monitoring. The system successfully demonstrated dynamic performance during both charging and discharging processes. Nevertheless, thermal output during the discharge phase was too small and unusable, which was proved suboptimal. Despite attempts to enhance performance through various strategies, the issue persisted, highlighting the difficulty of absorber design.

These early-stage prototypes illustrate both the promise and the complexity of translating ATB technologies into scalable, field-ready systems. Continued efforts in materials and manufacturing process engineering, heat and mass transfer optimization, and long-duration system testing will be essential for advancing ATBs toward widespread adoption. In 2014, Zhang et al.¹⁰⁰ developed an experimental prototype with 10 kWh cold storage capacity employing the H₂O/LiBr working pair (Figure 7E), marking a significant step forward in experimental validation of ATB technologies. The prototype featured a fully stainless-steel enclosure, including both the main shell and spray heat exchangers, ensuring chemical compatibility and corrosion resistance. Shield pumps were employed to drive the liquid circulation to facilitate the spray heat/mass transfer process. A key step in this work was the systematic vacuum sealing design. Leak rate testing revealed a vacuum tightness well below the threshold defined by Chinese national standards, confirming the superior hermeticity and establishing robust conditions for ATB operation. In addition to capturing detailed dynamic behavior during both charging and discharging processes, the study provided comprehensive storage performance data under three application scenarios: space cooling, domestic hot water supply, and space heating. The prototype successfully delivered chilled water at 7 °C, domestic hot water at 65 °C, and heating water at 43 °C. The corresponding ESDs were 42 kWh/m³, 88 kWh/m³, and 110 kWh/m³, respectively, while the ESEs reached 0.51, 0.97, and 1.03.

Later, several ATB prototypes incorporating advanced cycles have been developed to further explore performance optimization. Gao et al.⁵⁷ constructed a double-stage ATB prototype (Figure 7D), using 380 kg of LiBr solution (40%). The system was designed to enable detailed monitoring of dynamic temperature profiles across the heat transfer fluids during both charging and discharging processes. In the heating mode, the prototype demonstrated a marked dependence of ESD on evaporation temperature. When the evaporator operated between 12-15 °C, the system achieved an ESD of 67 kWh/m³; as the evaporation temperature increased to 15-18 °C, the ESD rose to 85 kWh/m³. A similar trend was observed in cooling mode: when the chilled water supply temperature was 11 °C, the ESD reached 66 kWh/m³, and increased to 81 kWh/m³ when the supply temperature rose to 13 °C.

Ding et al.⁴⁴ developed a two-stage ATB prototype (Figure 7C) using 40 kg of LiBr solution (50%), with a designed cold storage capacity of 5 kWh. Following a 72-hour pressure stabilization test, the system demonstrated excellent vacuum retention, maintaining a steady internal pressure at approximately 3.4 kPa, providing an essential working condition for closed-cycle operation. The study systematically characterized the dynamic behaviors across multiple parameters, including the temperatures of the solution, refrigerant, and thermal transfer fluids (hot and cold water), as well as internal pressure, flowrates, and real-time heat duties. Performance testing under various charging temperatures revealed that the two-stage configuration significantly enhanced ESD under lower-grade heat input conditions. Building upon this platform, the team extended their investigation to a two-stage ESHT,⁵⁵ capable of heat upgrading. Remarkably, with a heat source temperature of 70 °C, the prototype achieved output temperatures exceeding 90 °C. This result highlights the potential of multi-stage ESHT cycle not only to improve ESD but also to elevate thermal quality, thereby expanding the range of suitable applications, especially in low-grade heat recovery scenarios.

In recent years, three-phase ATB systems have attracted growing interest as a means to further elevate the ESD by leveraging solution crystallization. Lin et al.^{101, 102} developed an experimental prototype of a three-phase ATB (Figure 7F), initially charged with approximately 115 kg of LiCl solution at a concentration of 38%. To suppress premature crystallization and enhance solubility, ethylene glycol was introduced as an activating agent. The study provided a comprehensive characterization of dynamic behavior during both

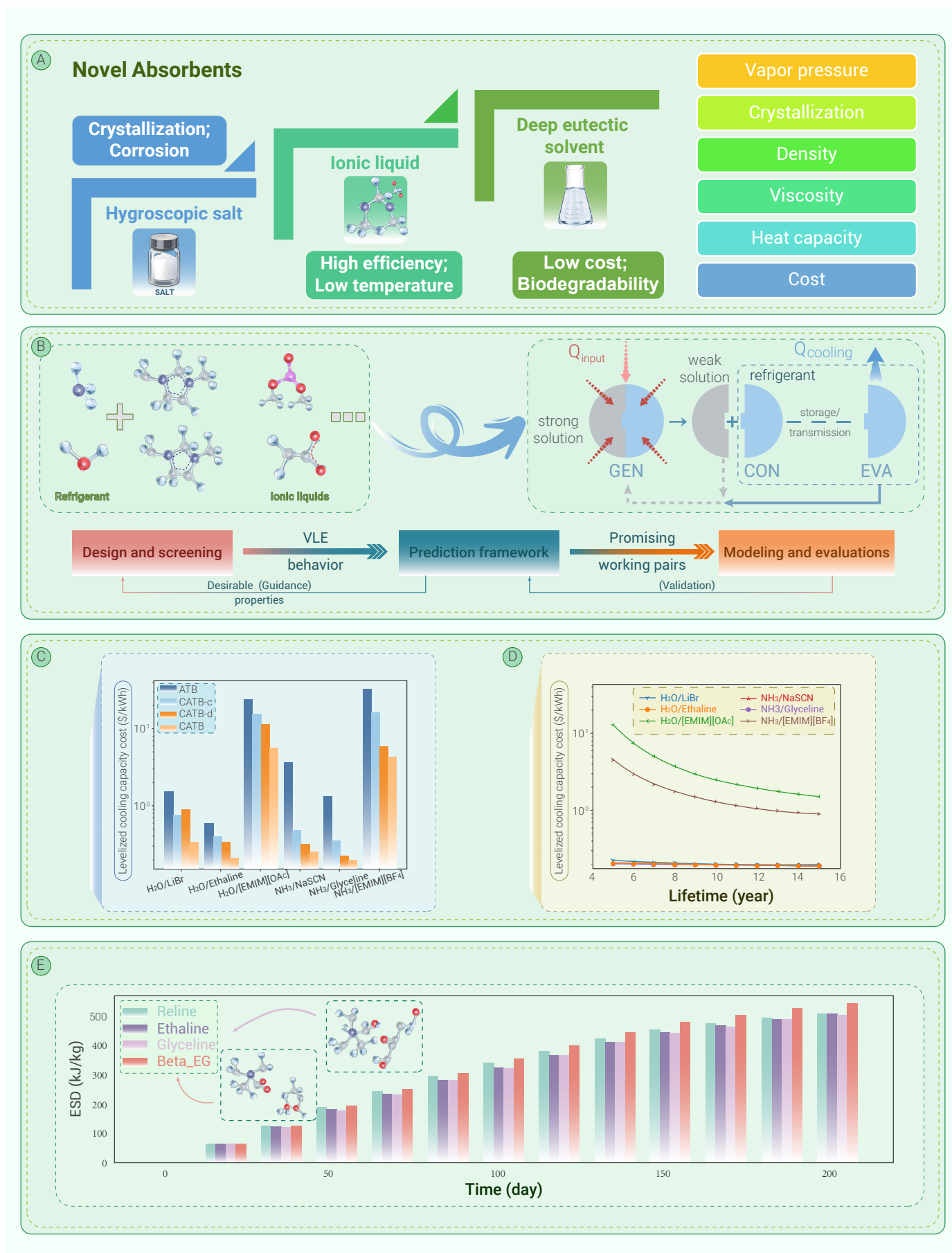


Figure 6. Performance evaluation of novel working fluids for absorption thermal batteries. (A) merits of novel working fluids and key thermophysical properties, (B) relating the thermophysical properties with cycle performance via the prediction framework,⁸¹ (C) levelized cost of storage of different ATB cycles and working fluids,⁶⁹ (D) levelized cost of storage of various working fluids with lifetime increasing,⁶⁹ (E) ESDs of DES-based working fluids for long-term energy storage.

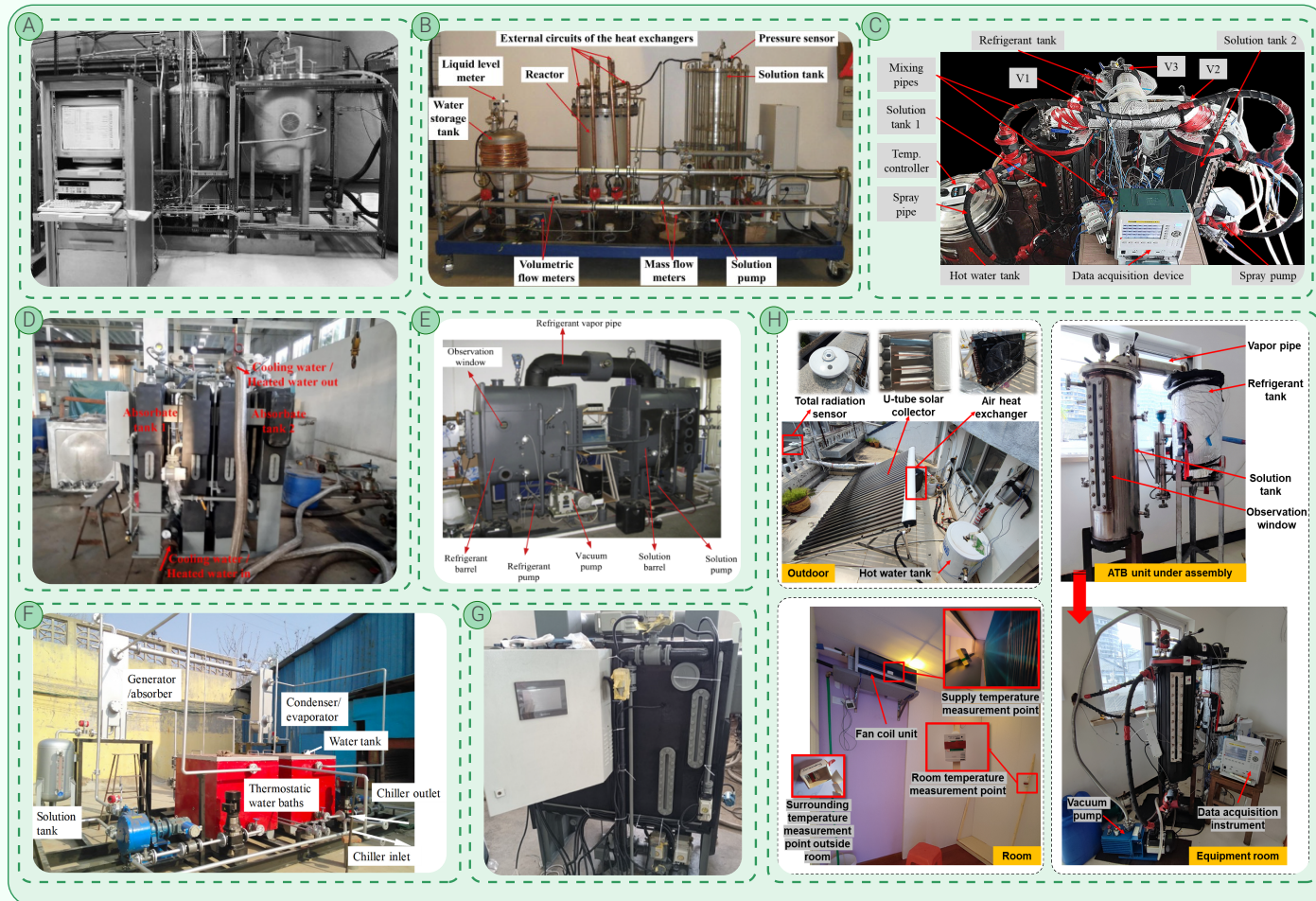


Figure 7. Development of ATB experimental prototype. (A) basic ATB using $\text{H}_2\text{O}/\text{NaOH}$, (B) 8 kWh basic ATB using $\text{H}_2\text{O}/\text{LiBr}$, (C) two-stage ATB using $\text{H}_2\text{O}/\text{LiBr}$, (D) double-stage ATB using $\text{H}_2\text{O}/\text{LiBr}$, (E) 10 kWh basic ATB using $\text{H}_2\text{O}/\text{LiBr}$, (F) three-phase ATB using $\text{H}_2\text{O}/\text{LiCl}$, (G) three-phase ATB using $\text{H}_2\text{O}/\text{LiBr}$, (H) solar-driven ATB for space heating system using $\text{H}_2\text{O}/\text{LiBr}$.

charging and discharging processes, alongside detailed assessments of storage performance. Due to the enhanced solubility facilitated by the additive, the system achieved substantial improvements in ESD, reaching 108–177 kWh/m^3 , which is an 18–48% increase relative to a baseline without the additive. Compared to conventional ATB cycles without crystallization, the three-phase cycle delivered an ESD enhancement of 19.3–80.3%, underscoring the transformative potential of crystallization-enabled storage in advancing ESD beyond current limits. You et al.¹⁰³ constructed a three-phase ATB prototype utilizing LiBr solution (Figure 7G), with a particular focus on addressing the operational challenges associated with salt crystallization. The system integrated a suite of crystallization mitigation strategies, including filtration, high-level solution intake, electric heating rod-based crystal remelting, and bypass flushing using refrigerant to prevent clogging and ensure stable operation. Experimental comparisons revealed a dramatic increase in ESD when leveraging the crystallization-enhanced three-phase cycle. Relative to conventional ATB, the measured ESD exhibited a 102–210% improvement, highlighting the considerable storage potential unlocked through crystallization processes.

Despite these promising results obtained in the experiment, crystal remelting and anti-blockage measures remain critical technical bottlenecks, particularly for long-term storage scenarios where system reliability and operational continuity are paramount. Future efforts will need to address the dynamic control of crystallization, the thermomechanical durability of crystallization-resistant components, and real-time adaptation strategies to fully harness the advantages of three-phase ATBs in practical applications.

To advance the real-world deployment of ATB technologies, Ding et al.¹⁰⁴ developed a solar-driven ATB system for space heating applications (Figure 7H). The demonstration system employed solar thermal collectors as the

primary heat source, an air heat exchanger as the cooling sink, and a fan coil unit as the thermal delivery terminal. Driven by the temperature gradient between the solar-heated fluid and the ambient environment, a compact ATB unit was designed and successfully implemented to provide room heating. With condensation heat recovery, the system maintained indoor temperatures above 20 °C for over 12 hours in both the charging and discharging processes, demonstrating both continuous and stable thermal output and extended duration. Notably, the experiment achieved record-high performance metrics: an ESD of 414.1 kWh/m^3 and an ESE of 1.21, marking the highest values reported to date in ATB experimentation. This application-oriented demonstration underscores the strong compatibility of ATBs with low-grade renewable heat sources and highlights their potential as a robust, long-duration thermal storage solution for distributed building-scale energy systems.

CONCLUSIONS AND PERSPECTIVES

ATB has emerged as a promising solution for efficient thermal utilization and renewable energy integration, offering unique advantages in matching energy supply and demand in both time and grade. This review has systematically examined the evolution of ATB technologies, spanning from fundamental cycle innovations, novel working pairs, and experimental prototype demonstrations. The conclusions are highlighted as follows:

1. Advanced ATB cycles, including double-stage, two-stage, compression-assisted, double-effect, double-effect compression-assisted, and PCM-assisted, have significantly improved ESD and ESE, extending the operational boundaries of ATBs into lower-temperature and broader application domains. Moreover, to address the challenge of energy quality mismatch, particularly when high-temperature output is required from low-grade heat

sources, the ESHT (type II ATB) concept was introduced. This temperature-lifting effect effectively upgrades the energy grade and allows ESHT to serve as both thermal storage and heat transformer devices, making them especially valuable in applications requiring high-grade heat output. In addition, a key barrier to practical deployment is the decline in discharging rate, caused by decreasing solution concentration. To mitigate this, dynamic discharge strategies such as multi-level ATB and variable flowrate control have been proposed. These methods stabilize the output by adaptively adjusting the input concentration or flowrate, ensuring that user demand is met throughout the discharge period. Such approaches have been validated to deliver over 12 hours of stable heating or cooling, substantially improving the temporal flexibility and user-aligned performance of ATBs.

2. The development of novel working fluids has significantly expanded the potential of ATBs with better energy storage performance. Ionic liquids (ILs), with crystallization-free nature and high absorption capacity, offer good energy storage performance and lower charging temperature, but their practical application is limited by high costs and complex synthesis. Deep eutectic solvents (DESSs), sharing similar thermophysical properties with ILs, further address these limitations through their low cost and biodegradability. DES-based ATBs achieve competitive ESE and low leveled cost of storage (LCOS), making them promising for short- and long-term energy storage. With continued progress in material screening, property modeling, and cycle performance investigation, ILs and DESSs are expected to play a critical role in enabling cost-effective and scalable ATB technologies.

3. Experimental prototyping has played a pivotal role in validating feasibility and accelerating the transition of ATB from concept to application. A series of lab- and field-scale prototypes—ranging from basic two-tank configurations to advanced double-stage, two-stage, and three-phase systems—have demonstrated the functional viability of ATBs for both heating and cooling applications. Concurrently, engineering strategies for vacuum sealing, heat and mass transfer optimization, and multi-mode control have facilitated the transition from conceptual design to functional prototypes. Field demonstrations coupling ATBs with solar heat sources have further confirmed their real-world viability and potential in building-scale energy systems.

Despite the remarkable progress in the development of ATB, several critical research frontiers remain open, offering substantial opportunities for advancing both the science and application of this promising thermal storage technology.

1. The current exploration of advanced cycles remains largely theoretical, with limited translation into experimental validation. Although a variety of cycle configurations, such as double-effect and compression-assisted systems, have demonstrated great potential in simulations, the lack of corresponding prototypes under realistic boundary conditions constrains their credibility and scalability. Future work should focus on developing robust experimental platforms capable of verifying the performance of these advanced cycles under multiple operating scenarios, including variable temperature gradients, intermittent charging sources, and long-duration discharge demands.

2. The development of high-performance, low-cost absorbent-refrigerant working pairs is pivotal to unlocking the full potential of ATBs. While emerging candidates such as ILs and DES have shown promise in specific aspects, e.g., crystallization-free and lower corrosion, they have yet to match the maturity and reliability of conventional salt-based solutions. Given the immense chemical design space, data-driven screening approaches, particularly those powered by artificial intelligence (AI) and molecular design, are expected to play a transformative role.

3. The multifunctionality of ATB, i.e., offering cooling, heating, or dehumidification, remains an underexplored advantage. While most research has centered on energy storage performance, emerging trends in energy-intensive domains such as high-density electronics, cold-chain logistics, and industrial waste heat recovery present a growing demand for flexible, dispatchable thermal solutions. Likewise, the urgent need for the building sector for high-efficiency heating, ventilation, and air conditioning (HVAC) systems aligns well with the attributes of ATBs. Future research should increasingly align with real-world application contexts, embedding ATB development within integrated energy systems and exploring techno-

economic pathways toward commercial viability.

4. Beyond thermodynamic performance, practical deployment of ATBs is increasingly constrained by engineering challenges. These include vacuum integrity during long-term operation, material corrosion induced by high-concentration absorbents, and system-level manufacturability and cost. Ensuring durable, low-leakage vacuum systems, selecting corrosion-resistant components, and developing scalable manufacturing processes will be key to translating laboratory advances into robust commercial solutions.

REFERENCES

- Wang C., Engels A. and Wang Z. (2018). Overview of research on China's transition to low-carbon development: The role of cities, technologies, industries and the energy system. *Renew. Sustain. Energy Rev.* **81**:1350–64. DOI:10.1016/j.rser.2017.05.099
- Sadeghi G. (2022). Energy storage on demand: Thermal energy storage development, materials, design, and integration challenges. *Energy Stor. Mater.* **46**:192–222. DOI:10.1016/j.ensm.2022.01.017
- Saher S., Johnston S., Esther-Kelvin R., et al. (2024). Trimodal thermal energy storage material for renewable energy applications. *Nature* **636**:622–6. DOI:10.1038/s41586-024-08214-1
- Durvasulu V., Balliet W.H., Lopez C.J., et al. (2024). Rationale for adding batteries to hydropower plants and tradeoffs in hybrid system operation: A review. *Renew. Sustain. Energy Rev.* **202**:114673. DOI:10.1016/j.rser.2024.114673
- Witter E., Dobson P., Akindipe D., et al. (2025). A review of Geological Thermal Energy Storage for seasonal, grid-scale dispatching. *Renew. Sustain. Energy Rev.* **218**:115761. DOI:10.1016/j.rser.2025.115761
- Costa E. (2022). *Renewables 2022: Global Status Report. REN21*.
- Zhang Y. and Wang R. (2020). Sorption thermal energy storage: Concept, process, applications and perspectives. *Energy Stor. Mater.* **27**:352–69. DOI:10.1016/j.ensm.2020.02.024
- Ding Z., Wu W. and Leung M. (2021). Advanced/hybrid thermal energy storage technology: material, cycle, system and perspective. *Renew. Sustain. Energy Rev.* **145**:111088. DOI:10.1016/j.rser.2021.111088
- James N., Huang R., Woods J., et al. (2025). Investigation of ventilation-coupled high energy density sensible thermal energy storage. *Appl. Energy* **387**:125576. DOI:10.1016/j.apenergy.2025.125576
- Xie B., Du S., Wang R., et al. (2024). Heat pump integrated with latent heat energy storage. *Energy Environ. Sci.* **17**:6943–73. DOI:10.1039/D4EE02350A
- Xu H., Han X., Hua W., et al. (2025). Progress on thermal storage technologies with high heat density in renewables and low carbon applications: Latent and thermochemical energy storage. *Renew. Sustain. Energy Rev.* **215**:115587. DOI:10.1016/j.rser.2025.115587
- Huang X., Hu R., Gao X., et al. (2024). Study on melting process of latent heat energy storage system by nano-enhanced phase change material under rotation condition. *Appl. Therm. Eng.* **247**:123040. DOI:10.1016/j.applthermaleng.2024.123040
- Huang X., Li Y., Lu L., et al. (2025). Numerical investigations on heat release performance of phase change mixture of paraffin and water. *Solar Energy Mater. Solar Cells* **280**:113266. DOI:10.1016/j.solmat.2024.113266
- Yang S., Shi H.Y., Liu J., et al. (2024). Supercooled erythritol for high-performance seasonal thermal energy storage. *Nat. Commun.* **15**:4948. DOI:10.1038/s41467-024-49333-7
- Geng L., Wang J., Yang X., et al. (2024). Synergistic enhancement of phase change materials through three-dimensional porous layered covalent triazine framework/expanded graphite composites for solar energy storage and beyond. *Chem. Eng. J.* **487**:150749. DOI:10.1016/j.cej.2024.150749
- Desai F., Prasad J.S., Muthukumar P., et al. Thermochemical energy storage system for cooling and process heating applications: A review. *Energy Convers. Manag.* **229**:113617. DOI:10.1016/j.enconman.2020.113617
- Wu W., Bai Y., Huang H., et al. (2019). Charging and discharging characteristics of absorption thermal energy storage using ionic-liquid-based working fluids. *Energy* **189**:116126. DOI:10.1016/j.energy.2019.116126
- Duffy A.M., Lockyear K.T., Hughes M.T., et al. (2025). Investigation of a novel combined ab-and ad-sorption based thermal energy storage and upgrade system. *Appl. Therm. Eng.* **258**:124520. DOI:10.1016/j.applthermaleng.2024.124520
- Fan Y., Zhang W., Chen S., et al. (2025). A solar adsorption thermal battery for seasonal energy storage. *Cell Rep. Phys. Sci.* **6**. DOI:10.1016/j.xcrp.2025.102467
- Zhang W., Mehari A., Zhang X., et al. (2023). Ammonia-based sorption thermal battery: Concepts, thermal cycles, applications, and perspectives. *Energy Stor. Mater.* **62**:102930. DOI:10.1016/j.ensm.2023.102930
- You J., Gao J., Li R., et al. Air-source heat pump assisted absorption heat storage for discharging under low ambient temperature. *Appl. Energy* **380**:125121. DOI:10.1016/j.apenergy.2024.125121
- Gao J., Xu Z. and Wang R. (2021). Towards high-performance sorption cold energy storage and transmission with ionic liquid absorbents. *Energy Convers. Manag.* **241**:114296. DOI:10.1016/j.enconman.2021.114296
- Zhou C., Lv F., Wan Z., et al. (2022). A double-effect/two-stage absorption refrigeration and thermal energy storage hybrid cycle using dual working fluids.

- Appl. Therm. Eng.* **214**:118858. DOI:10.1016/j.applthermaleng.2022.118858
24. Xu Z. and Wang R. (2022). High-performance absorption thermal storage with once-through discharging. *ACS Sustain. Chem. Eng.* **10**:720–30. DOI:10.1021/acssuschemeng.1c04370
25. Mehari A., Xu Z. and Wang R. (2020). Thermal energy storage using absorption cycle and system: A comprehensive review. *Energy Conver. Manag.* **206**:112482. DOI:10.1016/j.enconman.2020.112482
26. Hao Z., He G., Wu A., et al. (2025). Dynamic characteristics and performance enhancement of a novel hybrid system integrating transcritical CO₂ heat pump and absorption thermal energy storage. *Energy* **2025**:136874. DOI:10.1016/j.energy.2025.136874
27. Jeong J., Jung H.S., Lee J.W., et al. (2023). Hybrid cooling and heating absorption heat pump cycle with thermal energy storage. *Energy* **283**:129027. DOI:10.1016/j.energy.2023.129027
28. Wang L., Liu X., Yang Z., et al. (2020). Experimental study on a novel three-phase absorption thermal battery with high energy density applied to buildings. *Energy* **208**:118311. DOI:10.1016/j.energy.2020.118311
29. Zhai C. and Wu W. (2024). A compact modular microchannel membrane-based absorption thermal energy storage system for highly efficient solar cooling. *Energy* **294**:130783. DOI:10.1016/j.energy.2024.130783
30. Choi H.W., Jeong J. and Kang Y.T. (2024). Optimal discharging of solar driven sorption thermal battery for building cooling applications. *Energy* **296**:131087. DOI:10.1016/j.energy.2024.131087
31. Wang S., Deng Z., Chen H., et al. (2025). Fluctuation smoothing performance of wind-powered absorption chiller based on absorption thermal energy storage. *J. Energy Stor.* **121**:116480. DOI:10.1016/j.est.2025.116480
32. Choi H.W., Koo J.R. and Kang Y.T. (2025). Optimization of sorption thermal battery integrated with heat pump for plus energy building applications. *Energy Conver. Manag.* **332**:119693. DOI:10.1016/j.enconman.2025.119693
33. Min H., Choi H.W., Jeong J., et al. (2023). Daily sorption thermal battery cycle for building applications. *Energy* **282**:129016. DOI:10.1016/j.energy.2023.129016
34. Rubitherm. (2024). (accessed 12 Dec 2024). DOI:https://www.rubitherm.eu/
35. Limited PCMP. (2023). PCM Solutions. (accessed 27 November 2023). DOI:https://www.pcmproducts.net/
36. Hui L., N'Tsoukpoe K.E. and Lingai L. (2011). Evaluation of a seasonal storage system of solar energy for house heating using different absorption couples. *Energy Conver. Manag.* **52**:2427–36. DOI:10.1016/j.enconman.2010.12.049
37. Kerskes H., Mette B., Asenbeck S., et al. (2010). Experimental and numerical investigations on thermo chemical heat storage. *Eurosun 2010*. DOI:10.18086/eurosun.2010.16.14
38. Zondag H., Kikkert B., Smeding S., et al. (2013). Prototype thermochemical heat storage with open reactor system. *Appl. Energy* **109**:360–5. DOI:10.1016/j.apenergy.2013.01.082
39. Bales C., Gantenbein P., Jaenig D., et al. (2008). Laboratory tests of chemical reactions and prototype sorption storage units. *IEA Solar Heat. Cool. Program. Task. 32*. DOI:www.mendeley.com/catalogue/f0a889ce-00f0-3e58-8b3e-6f7f9d807b4f/
40. 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
41. Ding Z. and Wu W. (2024). A phase-change-material-assisted absorption thermal battery for space heating under low ambient temperatures. *Energy* **299**:131407. DOI:10.1016/j.energy.2024.131407
42. Xu Z. and Wang R. (2017). A sorption thermal storage system with large concentration glide. *Energy* **141**:380–8. DOI:10.1016/j.energy.2017.09.088
43. Xu Z. and Wang R. (2019). Absorption seasonal thermal storage cycle with high energy storage density through multi-stage output. *Energy* **167**:1086–96. DOI:10.1016/j.energy.2018.11.072
44. 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
45. Ding Z. and Wu W. (2025). Dynamic characteristics and performance enhancement of two-stage absorption thermal battery for long-term renewable energy storage. *Appl. Energy* **377**:124752. DOI:10.1016/j.apenergy.2024.124752
46. Wu W., Ding Z., Sui Y., et al. (2021). Comparative dynamic performance of hybrid absorption thermal batteries using H₂O/1, 3-dimethylimidazolium dimethylphosphate. *Energy Conver. Manag.* **228**:113690. DOI:10.1016/j.enconman.2020.113690
47. Ding Z. and Wu W. (2021). A hybrid compression-assisted absorption thermal battery with high energy storage density/efficiency and low charging temperature. *Appl. Energy* **282**:116068. DOI:10.1016/j.apenergy.2020.116068
48. Ding Z., Wu W., Chen Y., et al. (2020). Dynamic characteristics and performance improvement of a high-efficiency double-effect thermal battery for cooling and heating. *Appl. Energy* **264**:114768. DOI:10.1016/j.apenergy.2020.114768
49. Ding Z. and Wu W. (2022). A novel double-effect compression-assisted absorption thermal battery with high storage performance for thermal energy storage. *Renew. Energy* **191**:902–18. DOI:10.1016/j.renene.2022.04.071
50. Liu G., Ji D. and Markides C.N. (2024). Progress and prospects of low-grade thermal energy utilization technologies. *Appl. Therm. Eng.* **254**:123859. DOI:10.1016/j.applthermaleng.2024.123859
51. Ding Z. and Wu W. (2022). Type II absorption thermal battery for temperature upgrading: Energy storage heat transformer. *Appl. Energy* **324**:119748. DOI:10.1016/j.apenergy.2022.119748
52. Ding Z., Wu W., Huang S.M., et al. (2023). A novel compression-assisted energy storage heat transformer for low-grade renewable energy utilization. *Energy* **263**:125681. DOI:10.1016/j.energy.2022.125681
53. Wang C. and Bi Y. (2024). Dynamic characteristics and performance analysis of a double-stage energy storage heat transformer with a large temperature lift. *Energy* **308**:132963. DOI:10.1016/j.energy.2024.132963
54. Wang C. and Bi Y. (2025). A novel double absorption energy storage heat transformer for low-grade energy recovery. *J. Energy Stor.* **118**:116302. DOI:10.1016/j.est.2025.116302
55. Ding Z. and Wu W. (2025). Large-temperature-lift energy storage heat transformer for deep thermal energy utilization. *Appl. Energy* **384**:125481. DOI:10.1016/j.apenergy.2025.125481
56. Ding Z., Sui Y. and Wu W. (2025). Research Progress in Absorption Thermal Energy Storage. *J. Refrig.* **46**:11–23. DOI:10.12465/j.issn.0253-4339.2025.03.011
57. Gao J., Xu Z. and Wang R. (2020). Experimental study on a double-stage absorption solar thermal storage system with enhanced energy storage density. *Appl. Energy* **262**:114476. DOI:10.1016/j.apenergy.2019.114476
58. Ding Z. and Wu W. (2021). A hybrid compression-assisted absorption thermal battery with high energy storage density/efficiency and low charging temperature. *Appl. Energy* **282**:116068. DOI:10.1016/j.apenergy.2020.116068
59. Chen R., Lu D., Shen T., et al. (2025). Performance evaluation of an absorption thermal energy storage system: A new thermodynamic analysis method based on chemical potential. *J. Energy Stor.* **128**:117198. DOI:10.1016/j.est.2025.117198
60. Chen R., Lu D., Shen T., et al. (2025). A new dynamic control strategy for a solar-driven absorption thermal energy storage system: Modeling and performance evaluation. *Appl. Therm. Eng.* **260**:124983. DOI:10.1016/j.applthermaleng.2024.124983
61. 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
62. Ding Z. and Wu W. (2023). Dynamic discharging characteristics of absorption thermal battery under different capacity regulation strategies. *Energy Built. Environ.* **4**:341–53. DOI:10.1016/j.enbenv.2022.02.004
63. 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
64. Mehari A., Wang R. and Xu Z. (2022). Evaluation of a high-performance evaporative cooler-assisted open three-phase absorption thermal energy storage cycle for cooling. *Appl. Energy* **325**:119818. DOI:10.1016/j.apenergy.2022.119818
65. Hernández J., Rivera W., Colorado D., et al. (2012). Optimal COP prediction of a solar intermittent refrigeration system for ice production by means of direct and inverse artificial neural networks. *Solar Energy* **86**:1108–17. DOI:10.1016/j.solener.2011.12.021
66. Altamirano A., Le Pierrès N. and Stutz B. (2019). Review of small-capacity single-stage continuous absorption systems operating on binary working fluids for cooling: Theoretical, experimental and commercial cycles. *I. J. Refrig.* **106**:350–73. DOI:10.1016/j.jrefrig.2019.06.033
67. Cai D., Jiang J., He G., et al. (2016). Experimental evaluation on thermal performance of an air-cooled absorption refrigeration cycle with NH₃–LiNO₃ and NH₃–NaSCN refrigerant solutions. *Energy Conver. Manag.* **120**:32–43. DOI:10.1016/j.enconman.2016.04.089
68. Wu W., Wang B., Shi W., et al. (2013). Crystallization analysis and control of ammonia-based air source absorption heat pump in cold regions. *Adv. Mech. Eng.* **5**:140341. DOI:10.1155/2013/140341
69. 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
70. Sui Y., Zhai C., Wu W., et al. (2022). Multi-scale Computer-aided molecular design of ionic liquid for absorption heat transformer based on Machine learning. *Energy Conver. Manag.* **261**:115617. DOI:10.1016/j.enconman.2022.115617
71. Zuo G., Zhao Z., Yan S., et al. (2010). Thermodynamic properties of a new working pair: 1-Ethyl-3-methylimidazolium ethylsulfate and water. *Chem. Eng. J.* **156**:613–7. DOI:10.1016/j.cej.2009.06.020
72. Zhou T., Gui C., Sun L., et al. (2023). Energy applications of ionic liquids: recent developments and future prospects. *Chem. Rev.* **123**:12170–253. DOI:10.1021/acs.chemrev.3c00391
73. Faizan M., Ahmed R. and Ali H.M. (2021). A critical review on thermophysical and electrochemical properties of ionic liquids (nanoparticles dispersed in ionic liquids) and their applications. *J. Taiwan Ins. Chem. Eng.* **124**:391–423. DOI:10.1016/j.jtice.2021.02.004
74. Koutsoukos S., Philippi F., Malaret F., et al. (2021). A review on machine learning algorithms for the ionic liquid chemical space. *Chem. Sci.* **12**:6820–43. DOI:10.1039/D1SC01000J
75. Sen M. and Paolucci S. (2006). The use of ionic liquids in refrigeration. *ASME IMECE* :131–4. DOI:10.1115/IMECE2006-14712

76. Yokozeki A. and Shiflett M.B. (2007). Vapor–liquid equilibria of ammonia+ionic liquid mixtures. *Appl. Energy* **84**:1258–73. DOI:10.1016/j.apenergy.2007.02.005
77. Yokozeki A. and Shiflett M.B. (2010). Water Solubility in Ionic Liquids and Application to Absorption Cycles. *Ind. Eng. Chem. Res.* **49**:9496–503. DOI:10.1021/ie1011432
78. Zhang X. and Hu D. (2011). Performance simulation of the absorption chiller using water and ionic liquid 1-ethyl-3-methylimidazolium dimethylphosphate as the working pair. *Appl. Therm. Eng.* **31**:3316–21. DOI:10.1016/j.applthermaleng.2011.06.011
79. Hansen B.B., Spittle S., Chen B., et al. (2021). Deep Eutectic Solvents: A Review of Fundamentals and Applications. *Chem. Rev.* **121**:1232–85. DOI:10.1021/acs.chemrev.0c00385
80. Boman D.B., Hoysall D.C., Staedter M.A., et al. (2017). A method for comparison of absorption heat pump working pairs. *J. J. Refrig.* **77**:149–75. DOI:10.1016/j.jrefrig.2017.02.023
81. Gao J.T., Xu Z.Y. and Wang R.Z. (2021). Towards high-performance sorption cold energy storage and transmission with ionic liquid absorbents. *Energy Conver. Manag.* **241**:114296. DOI:10.1016/j.enconman.2021.114296
82. Gao J. and Xu Z. (2022). Performance evaluation of absorption thermal energy storage/transmission using ionic liquid absorbents. *Energy Built. Environ.* **4**. DOI:10.1016/j.enbenv.2022.01.001
83. Wu W., Ding Z.X., Sui Y.R., et al. (2021). Comparative dynamic performance of hybrid absorption thermal batteries using H₂O/1,3-dimethylimidazolium dimethylphosphate. *Energy Conver. Manag.* **228**. DOI:10.1016/j.enconman.2020.113690
84. 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
85. Sui Y.R., Zhai C., Wu W., et al. (2022). Multi-scale Computer-aided molecular design of ionic liquid for absorption heat transformer based on Machine learning. *Energy Conver. Manag.* **261**:115617. DOI:10.1016/j.enconman.2022.115617
86. Sui Y., Zhai C., Lin H., et al. (2023). How to rationally screen refrigerant/ionic liquids for thermal cooling: A multi-criteria approach based on machine learning. *Energy Conver. Manag.* **282**:116853. DOI:10.1016/j.enconman.2023.116853
87. Mehari A., Xu Z.Y. and Wang R.Z. (2020). Thermal energy storage using absorption cycle and system: A comprehensive review. *Energy Conver. Manag.* **206**. DOI:10.1016/j.enconman.2020.112482
88. Liu Y., Friesen J.B., McAlpine J.B., et al. (2018). Natural Deep Eutectic Solvents: Properties, Applications, and Perspectives. *J. Nat. Prod.* **81**:679–90. DOI:10.1021/acs.jnatprod.7b00945
89. Abo-Hamad A., Hayyan M., AlSaadi M.A., et al. (2015). Potential applications of deep eutectic solvents in nanotechnology. *Chem. Eng. J.* **273**:551–67. DOI:10.1016/j.cej.2015.03.091
90. Deng D.S., Gao B., Zhang C., et al. (2019). Investigation of protic NH₄SCN-based deep eutectic solvents as highly efficient and reversible NH₃ absorbents. *Chem. Eng. J.* **358**:936–43. DOI:10.1016/j.cej.2018.10.077
91. Dai Y., van Spronsen J., Witkamp G.J., et al. (2013). Natural deep eutectic solvents as new potential media for green technology. *Analyt. Chim. Acta.* **766**:61–8. DOI:10.1016/j.aca.2012.12.019
92. Abedin R., Heidarian S., Flake J.C., et al. (2017). Computational Evaluation of Mixtures of Hydrofluorocarbons and Deep Eutectic Solvents for Absorption Refrigeration Systems. *Langmuir* **33**:11611–25. DOI:10.1021/acs.langmuir.7b02003
93. Abedin R., Shen Y., Flake J.C., et al. (2020). Deep Eutectic Solvents Mixed with Fluorinated Refrigerants for Absorption Refrigeration: A Molecular Simulation Study. *J. Phys. Chem. B* **124**:4536–50. DOI:10.1021/acs.jpbc.0c01860
94. Haghighbakhsh R., Peyrovedin H., Raeissi S., et al. (2020). Investigating the performance of novel green solvents in absorption refrigeration cycles: Energy and exergy analyses. *J. J. Refrig.* **113**:174–86. DOI:10.1016/j.jrefrig.2020.01.013
95. Haghighbakhsh R., Peyrovedin H., Raeissi S., et al. (2020). Energy Conservation in Absorption Refrigeration Cycles Using DES as a New Generation of Green Absorbents. *Entropy (Basel)* **22**:409. DOI:10.3390/e22040409
96. Nessakh F.Z., Mutelet F. and Negadi A. (2022). Efficiency of two working fluids constituted of a deep eutectic solvent and water in absorption heat transformer. *J. J. Energy Res.* **46**:23578–94. DOI:10.1002/er.8658
97. Sui Y., Ding Z., Sui Z., et al. (2025). Seasonal Thermochemical Energy Storage with Affordable and High-Energy-Density Deep Eutectic Solvents. *Appl. Energy* **386**:125577. DOI:10.1016/j.apenergy.2025.125577
98. Weber R. and Dorer V. (2008). Long-term heat storage with NaOH. *Vacuum* **82**:708–16. DOI:10.1016/j.vacuum.2007.10.018
99. N'Tsoukpoe K., Le Pierrès N. and Luo L. (2013). Experimentation of a LiBr–H₂O absorption process for long-term solar thermal storage: Prototype design and first results. *Energy* **53**:179–98. DOI:10.1016/j.energy.2013.02.023
100. Zhang X., Li M., Shi W., et al. (2014). Experimental investigation on charging and discharging performance of absorption thermal energy storage system. *Energy Conver. Manag.* **85**:425–34. DOI:10.1016/j.enconman.2014.05.100
101. Lin Y., Xiao F., Wang S., et al. (2024). Experimental study on a closed absorption thermal energy storage system using modified LiCl solution for enhancing energy storage density. *J. Energy Stor.* **103**:114551. DOI:10.1016/j.est.2024.114551
102. Lin Y., Xiao F., Wang L., et al. (2024). Experimental investigation and performance evaluation of a closed three-phase absorption thermal energy storage system. *Energy* **313**:134038. DOI:10.1016/j.energy.2024.134038
103. You J., Gao J., Wang R., et al. (2024). High-density and anti-clogging three-phase absorption heat storage with crystallization management. *Appl. Energy* **376**:124240. DOI:10.1016/j.apenergy.2024.124240
104. Ding Z., Sui Y., Sui Z., et al. (2025). Solar-driven hygroscopic-material-based absorption thermal battery for global heating decarbonization. *Energy Stor. Mater.* **77**:104184. DOI:10.1016/j.ensm.2025.104184

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 JCYJ20240813153108012), and the Research Grants Council of Hong Kong (CityU 11218922).

AUTHOR CONTRIBUTIONS

All authors contributed to the manuscript and approved the final version

DECLARATION OF INTERESTS

The authors declare no competing interests.

DATA AND CODE AVAILABILITY

Data are available from the corresponding author upon reasonable request.