



RESEARCH ARTICLE

A REVIEW OF SOLAR ABSORPTION REFRIGERATION TECHNOLOGY RESEARCH

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ABSTRACT

Against the backdrop of global energy transition, solar absorption refrigeration faces both opportunities and challenges. Currently, single-effect and double-effect systems using water-lithium bromide as the working pair dominate, but they suffer from issues such as crystallization, corrosion, and low energy efficiency. New working pairs like ionic liquids are limited by high viscosity and cost. The technology has a small application scale, with market penetration below 3%, investment costs more than three times those of electric refrigeration, payback periods exceeding nine years, and research primarily focused on regions with high solar irradiance. Vacuum tubes are suitable for medium- and low-temperature single-effect configurations, while troughs are better suited for high-temperature double-effect setups. Due to significant fluctuations in radiation and time-consuming thermal storage, it is recommended to accelerate the engineering validation of new working fluids, develop absorption-compression hybrid cycles, promote multi-grade energy coupling, and conduct field studies across different climate zones.

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INTRODUCTION

Currently, as climate change presents increasingly severe challenges, countries around the world are proactively adjusting their energy structures to mitigate the greenhouse effect and its associated environmental issues. Thompson (2023), through a systematic literature review on the transition to renewable electricity, reached a key finding: so far, renewable energy has not effectively replaced fossil fuels but has instead objectively stimulated additional energy demand. Given this observation, despite the growing share of renewables in global power generation in recent years, global greenhouse gas emissions continued to rise steadily in 2021 (1). As for how the renewal energy is used right now we can't say there is any great change or large switch it means that fossil fuel is still mostly playing its role within the energy use system. As for China, Zheng, et al. (2020) discovered that in the span of 1978-2018 China's total CO₂ emissions grew by about 6X's amount. According to the driving factors decomposition point of view, economic growth is responsible for adding 176% towards emissions rise, with population growth adding 16%. But energy intensity has decreased by 79%, carbon intensity down 13 per cent, it slowed the whole rate of emissions growth (2). And also this shows the very important place of the policies at the macro level in influencing the emission drivers. And all these global and Chinese context

info is a must if we ever wanna do an in-depth look at the decarb routes and strat in end-use energy sec. Specifically, in the end-use energy field of building cooling, its current development is at a critical juncture where structural contradictions and transformation opportunities intersect. Due to the high temporal matching and natural physical compatibility between solar energy supply and building cooling demand in summer, solar-driven cooling technologies have unique application advantages compared to other technical routes. Mori et al. (2026) further pointed out that if fossil fuels are to be phased out under the premise of achieving the global 1.5°C temperature control target, the required electricity supply scale will be 1.6 to 1.8 times higher than the conventional cost-optimal path, and investment in the energy supply sector may increase by up to 34% (3). Regarding the technical branch of solar air conditioning technology, it is usually divided into two categories based on the form of driving energy: one is the electric-driven system, and the other is the heat-driven system. In recent years, numerous studies on absorption refrigeration systems have shown that performance parameters of such systems, such as the coefficient of performance, are core indicators for evaluating their technical feasibility and economic rationality. Meanwhile, these systems have shown good prospects for engineering promotion in application scenarios such as industrial cooling and district centralized cooling (4). Against the macro background of

advancing China's carbon neutrality goal, Yu et al. (2023) conducted research using a multi-region collaborative optimization model. The results showed that adopting a collaborative emission reduction strategy based on the regional maturity index can reduce the cumulative GDP loss by 1.54% and benefit more than 90% of China's provincial-level administrative regions. Based on the above model results, they suggested that economically developed regions such as Beijing, Shanghai, and Guangdong should peak carbon emissions by 2027; while resource-based or heavy industry-intensive regions such as Hebei, Shanxi, and Inner Mongolia can appropriately delay the peak time to around 2034 (5). Similarly, the vast Global South countries (i.e., developing countries and emerging economies) also face their own unique difficulties and challenges in the energy transition process. Heras and Gupta (2024) pointed out that the current deployment model of renewable energy in the Global South is more incremental expansion rather than transformative replacement. Nevertheless, this region still has great potential for leapfrog development and is expected to avoid repeating the high-carbon development path once taken by developed countries (6). Zhang et al. (2022) further pointed out that orderly promotion of the power sector transformation is conducive to achieving a socially just transition, and its net employment effect is positive; however, if countries continue to invest in new coal-fired power projects under their post-COVID-19 economic stimulus plans, thereby delaying necessary transition actions, up to 90% of coal-fired power industry workers will face the risk of unemployment between 2030 and 2040, even though the renewable energy sector can fully offset these lost jobs (7).

To sum up, when conducting research on solar absorption refrigeration technology, it is necessary to closely integrate macro backgrounds such as global energy structure transformation, the reality of unbalanced development between different regions, and socially just transition, and conduct systematic and comprehensive considerations. Based on the above understanding, this review systematically introduces and comments on existing research in the field of solar absorption refrigeration around four key technical dimensions: unit configuration, working fluid pairs, application scale, and heat collection methods.

RESEARCH STATUS

Absorption Refrigeration Unit: Lithium bromide-water systems are currently the most widely used working fluid pair in absorption refrigeration. Solar-powered lithium bromide-water absorption refrigeration primarily employs water and lithium bromide as the working fluids, offering good performance and environmental benefits, although it is prone to issues such as crystallization and corrosion (8). Absorption chillers can be classified into single-effect, double-effect, triple-effect, and hybrid cycle types based on the temperature of the driving heat source (9). For solar lithium bromide absorption refrigeration systems, their performance is closely related to the temperature of the driving heat source. Generally, a relatively high heat source temperature can generally be achieved at around 80°C to 100°C, resulting in a coefficient of performance of approximately 0.7. In contrast, double-effect absorption chillers require a higher heat source temperature of about 140°C, and even under optimal control conditions, their COP can reach up to 1.2 (10-11). Zhang Shu believes that single-effect and double-effect units have lower refrigeration

efficiency compared to vapor compression systems, while triple-effect and multi-effect units, although more energy-efficient, are still in the experimental stage and have not yet achieved commercialization (9). According to Zhang Liying, when the heat source is below 80°C, the COP of a two-stage cycle is very low; therefore, researchers have proposed using combined cycles, including single-effect/two-stage, single-effect/three-stage, 1.x-stage, 1.5-effect, and EAX configurations. The specific method involves switching the variable-effect unit to different modes for solar energy utilization; triple-effect, pressurized, and composite triple-effect systems all have higher COPs, with pressurization slightly sacrificing efficiency but reducing generator temperature (12). Global revenue from solar absorption cooling is expected to reach approximately 13.29 billion yuan in 2025 and grow to 18.03 billion yuan by 2032, increasing at an annual rate of 4.4%; traditional compression refrigeration still accounts for over 97% of the market (13). Currently, most commercial installation projects and related research involve single-effect units combined with low-temperature collectors, while the integration of high-temperature collectors with multi-effect units remains relatively rare (11). This is because multi-effect units require higher heat source temperatures, more complex systems, and higher initial investment (14).

Absorption Working Fluid Pair: The core issue in absorption refrigeration systems lies in the proper matching between the refrigerant and the absorbent. Currently, the commercially available working fluid pairs for absorption refrigeration mainly include two routes: water-lithium bromide and ammonia-water. Bao Yangzheng et al. (2024) pointed out through a comprehensive review that the water-lithium bromide model, using water as the refrigerant and lithium bromide as the absorbent, has prominent advantages such as non-toxicity, environmental friendliness, and good thermodynamic performance, making it the most widely used aqueous working fluid pair in today's air conditioning field (15); Ammonia-water systems use ammonia as the refrigerant and water as the absorbent, enabling a wider cooling temperature range that meets the requirements of refrigeration and certain industrial processes (16). In addition to conventional absorption systems, new working fluid pairs have attracted increasing attention from researchers. Bian Yifeng et al. (2015) classified absorption working fluid pairs into five categories: ammonia, water, alcohols, chlorofluorocarbons, and others, and summarized the performance and potential of novel working fluid pairs such as NH_3/NaSCN , $\text{NH}_3/\text{LiNO}_3$, mixed salts, alcohols, and ionic liquids (17). Due to their outstanding advantages such as extremely low vapor pressure, non-flammability, and strong thermal stability (18), new working fluid pairs have been considered as alternatives to conventional absorbents and have attracted considerable attention in recent years. Regarding organic working fluid pairs, attempts have been made to combine HFCs with organic solvents for single-effect cycles to evaluate their potential to replace traditional working fluid pairs (19). Based on existing research, new working fluid pairs based on organic solvents and ionic liquids have been further explored. Wang Xiaopo et al. analyzed the feasibility of using $\text{NH}_3/(\text{omim})\text{BF}_4$ as a novel working fluid pair to replace $\text{NH}_3/\text{H}_2\text{O}$ (20). Bao Yangzheng et al. (2024) systematically reviewed the thermodynamic properties of novel working fluid pairs, such as ionic liquids and deep eutectic solvents, from the perspective of absorbents, including both computational and experimental methods (15). Overall, research on new working fluid pairs has primarily focused on

four aspects: compatibility with low-grade heat sources, environmental friendliness, high efficiency, and stability. Absorption refrigeration working fluid pairs are currently undergoing a transition from traditional binary systems to novel multi-component systems.

Application Scale: The application of solar absorption cooling and air conditioning is growing rapidly worldwide, with broad market prospects, yet penetration remains low, and true large-scale commercialization is still underway. Bian Yifeng et al. (2015) pointed out that cost issues and technical bottlenecks have restricted the commercial application of solar absorption refrigeration (17); Ali et al. (2024) pointed out that due to factors such as high initial costs and difficulties in maintenance, solar absorption refrigeration technology has been relatively limited in commercial applications and has not yet achieved large-scale deployment (21). Kritsnakriengkrai et al. (2024) pointed out through a field study conducted in Thailand that although the technology has advantages, its adoption remains low and the situation of limited commercialization has not changed. A survey of 52 stakeholders revealed that the main barrier currently is the high investment cost and excessively long payback period (22).

Mustafa et al. (2021) pointed out that when applying solar absorption cooling technology to small and medium-sized buildings, the following conclusions can be drawn: single-effect systems using vacuum tube or flat-plate collectors have become relatively mature and economically viable under Mediterranean and subtropical climatic conditions (23). Gunawan et al. (2024) conducted a quantitative analysis of the cooling capacity of these systems through extensive experiments and simulation methods. Their results indicated that single-effect units have a cooling capacity of 5-2 kW, while double-effect units achieve a cooling capacity of 1163 kW. They also found that the performance of such air-cooling systems has approached that of water-cooling systems, offering a practical pathway for water conservation in arid regions; at the same time, they recommended developing a regional standardized design guideline. This aligns with Mustafa et al.'s (2021) advocacy for forward promotion (24). Bian Yifeng et al. (2015) and Kritsnakriengkrai et al. (2024) both pointed out that high investment costs and long payback periods are major barriers to commercialization. Mustafa et al. (2021) and Gunawan et al. (2024), through scenario-specific adaptations, demonstrated that the system has already reached a relatively mature stage in terms of technology and economics. The practical implication of these two sets of studies is to highlight an issue: we have technically made progress, but we have not yet kept pace with the market.

Heat Collection Method: Vacuum tube collectors are suitable for medium- and low-temperature single-effect applications, while parabolic trough collectors are better suited for high-temperature double-effect systems; combining both enables preheating and high-temperature heat supply. In a comparison of the performance of four types of collectors—flat plate, vacuum tube, compound parabolic, and parabolic trough—in medium- and low-temperature cooling scenarios, Li Jing, Zhu Chuansheng et al. (2018) found that the vacuum tube collector system demonstrated the best overall performance based on indicators such as average energy cost, dynamic payback period, and exergy efficiency, with costs decreasing as installed capacity and solar irradiance increase (25). Cheng Youliang et al. (2022) verified that in regions with average

solar resources, the solar fraction of vacuum tube single-effect systems reaches a maximum of 39.9%, while the COP of parabolic trough single-effect systems reaches 1.297, making them more suitable for high-temperature applications (26). It has certain advantages in high-temperature double-effect refrigeration. Al-Widyan et al. (2026) studied a parabolic trough collector combined with phase change thermal storage driving a double-effect lithium bromide system, which can provide heat sources at 115-220°C under strong solar conditions in Jordan, with a COP of 1.2-1.4 and a payback period of approximately 8 years (27). A novel resolution for both medium and low-temperature preheating along with high-temperature energy supply. Karabuga (2025) proposed a combined system integrating vacuum tube heat pipe collectors and parabolic trough collectors for multi-generation applications, where the vacuum tube heat pipe collectors are used for medium- and low-temperature preheating, while the latter provides temperatures of 110-120°C, simulating a high-temperature heat source at 170°C, achieving an overall energy efficiency of 12.25% and an exergy efficiency of 9.85% (28). From these perspectives, this paper concludes that vacuum tube collectors are currently the most economical and stable option among low- to medium-temperature single-effect collectors; parabolic trough collectors are suitable for high-temperature double-effect cooling; and their cascaded series configuration can achieve maximum energy efficiency, shifting our approach from simply selecting the best collector to prioritizing high-temperature applications and then combining them for enhanced performance.

LIMITATIONS OF THE STUDY

Absorption Refrigeration Unit: The water-lithium bromide system suffers from strong corrosiveness, easy crystallization, and low cycle performance (15,29). Since lithium bromide solution tends to precipitate crystals under high temperature and high concentration, there is a risk of pipe blockage (30). Non-condensable gases will also be present, leading to poor system performance (31). Single-effect and double-effect units have low COPs and perform worse compared to vapor-compression systems; triple-effect and multi-effect units offer higher efficiency but are more complex and less economically viable, so simulation remains the primary approach. Single-effect methods can utilize low-grade heat, but their application is limited due to crystallization constraints and they cannot operate efficiently at high temperatures. Solar absorption refrigeration systems are problematic due to the high initial investment costs, intermittent solar supply, and difficulties in integrating and matching load (32).

Absorption Working Fluid Pair: At the level of conventional working fluid pairs, Bao Yangzheng et al. (2024) observed that water-lithium bromide solutions suffer from strong corrosibility, easy crystallization, and poor refrigeration (15). The ammonia-water system does face many problems in commercial usage; some reviews suggest that this working fluid pair is toxic, high operating pressure, and requires additional distillation machines which are also complex and more hazardous (33). On the aspect of new working fluid pairs, a review by Bao Yangzheng et al. (2024) pointed out that for new working fluid pair systems, the poor ability of the solution to absorb refrigerant vapor is a common issue (15). The high viscosity of ionic liquids often results in a smaller mass diffusion coefficient, creating significant mass transfer resistance, a problem that remains unresolved in absorption refrigeration systems (34).

Application Scale: Bian Yifeng et al. (2015) clearly concluded (given the state of the art at the time) that commercialization prospects of this technology were limited (17), while Mustafa et al. (2021) offered a more optimistic assessment of the potential of this kind of technology. However, since in their research they focus on a region with high solar irradiance such as Mediterranean and subtropical areas, and this is still poorly studied and investigated as low sunlight, high humidity or cold conditions (23). Hasan et al (2024) have noted that COP can change with changes in the irradiating of the system, from 0.57 and 0.74 which makes it hard to standardize design and implementation in different areas. Furthermore, the original investment was \$984.32/kW with a 9.91yr static payback period which is very limiting to the commercial adoption of the technology (35). Altork and Salem et al. (2024) also pointed out that 1,350 are still in full-fledged operation worldwide which is far from being available; The first total investment is \$2,153 per kilowatt of cooling capacity, more than three times the demand of existing electric cooling systems, and payback is longer than nine years with subsidies. Without subsidies the payback time may be longer than the equipment life span, which leads to a net overall poor performance (36).

Heat Collection Method: The solar radiation itself is always changing, causing the temperature at the collector outlet to become unstable. With fixed window-circulation time, absorption refrigerators do not always cooperate within the optimum COP, leading to low system energy efficiency and cooling stability (37). Seasonal thermal energy storage systems based on phase change materials may transfer thermal heat loads to seasons by themselves, but high integration complexity and high initial investment costs both impede their large-scale application in district heating and cooling (38). In solar heating systems, there is a mismatch between the variability of solar radiation and the seasonality of thermal load. However, as for the existing work, there seems to be no detailed knowledge of the dynamic response of the system at the high-level time scale (39).

REGARDING THE SHORTCOMINGS, I WOULD LIKE TO OFFER SEVERAL SUGGESTIONS: Given the crystallization and corrosion problems of the water-lithium bromide working pair, it is necessary to initiate experimental research on new absorbents such as ionic liquids and mixed refrigerants without delay. Most current thermodynamic simulation and property measurement work is short-term, and little in-depth research has been conducted on mass transfer resistance caused by high viscosity and cost. Therefore, long-term testing is still needed. In absorption refrigeration systems, it is common that cycle structures exhibit lower efficiencies when the working state changes. A hybrid cycle combining absorption and compression is considered a good solution. Examples include systems with compression-assist devices or ejectors, which allow switching between various cycle configurations. This increases the range of usable heat sources throughout operation and provides additional energy during partial-load or off-design conditions, while also adapting to ambient fluctuations. Reducing the cost and complexity of thermal energy storage integration remains an important goal to make the technology viable. Unlike thermochemical storage, which aims to achieve seasonal storage but suffers from insufficient cycle stability, the proposed approach can help integrate solar, geothermal, and industrial waste heat at multiple levels, thereby reducing the reliance on a single thermal storage unit and improving economic performance.

System climate adaptability should not be limited to high-solar-radiation areas but extended to various regions. A system selection map should include arid, temperate, monsoon, and high-latitude areas. Simulations should consider parameters such as solar irradiance, ambient temperature, and water demand under different weather conditions. Furthermore, deployment potential for low-insolation regions also needs to be evaluated.

DISCUSSION

In summary, technology is moving from demo/validation to early stages of commercialization and we need 4 things: engineer the new working fluids, work on hybrid cycles, get good at cheap heat storage, and field test across different climates.

CONCLUSION

Single-effect and double-effect systems are currently the main types used in commercial applications. However, single-effect systems have relatively low COP values, while double-effect systems require higher thermal energy input. Although triple-effect systems and combined cycles offer higher energy efficiency, they struggle to balance system complexity with economic feasibility. The absorption-compression hybrid cycle holds promise for overcoming energy efficiency bottlenecks under variable operating conditions. The water-lithium bromide working pair faces issues related to crystallization and corrosion, while the ammonia-water system is limited by safety concerns and scalability challenges. Ionic liquids show potential as alternatives, but their high viscosity, elevated cost, and lack of long-term operational validation remain barriers. Research efforts need to shift from thermodynamic modeling to system-level experimental studies. The market penetration of solar absorption cooling technology is less than 3%, and most research has focused on regions with high solar irradiance, while only a few studies have been conducted in areas with low solar radiation, high humidity, or cold climates; therefore, it is necessary to establish a system selection map across different climatic zones. Vacuum tube collectors are suitable for medium- and low-temperature single-effect systems, while parabolic trough collectors are better suited for high-temperature double-effect systems. The two can be connected in series to enhance efficiency. However, challenges remain, including significant fluctuations in solar radiation, high thermal storage costs, limited coupling research, and insufficient data in certain regions, all of which need to be addressed.

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