

Current and Future Trends in Solar-Powered Absorption and Adsorption Cooling Systems and Waste Heat

Muustafa Abdalla Othmam

Department of Refrigeration and Air Conditioning, Higher Institute of Engineering and Technology, Bani Walid, LIBYA

Corresponding author: mustafa20.20musbah@gmail.com



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ABSTRACT

Conventional vapor compression cooling systems impose significant burdens on energy grids and contribute to environmental degradation due to the use of high global warming potential (GWP) refrigerants. This review aims to analyze the current and future trends in alternative thermal cooling systems, specifically Absorption and Adsorption refrigeration, as sustainable solutions utilizing low-grade solar energy and waste heat. The review covers the fundamental operating principles and discusses recent advancements in improving the Coefficient of Performance (COP) through the development of multi-effect cycles and the use of advanced working pairs and sorbent materials (such as Metal-Organic Frameworks – MOFs). It also highlights strategies for efficiently integrating these systems with renewable and wasted thermal energy sources. The findings indicate a notable improvement in the efficiency of thermal units, yet challenges persist concerning initial capital cost and operational size. The study concludes by identifying key research gaps necessary for the widespread commercialization of these technologies, underscoring their pivotal role in achieving a sustainable cooling future.

Keywords- Solar cooling, absorption cooling, adsorption cooling, waste heat, energy efficiency, metal-organic frameworks (MOFs).

I. INTRODUCTION

The Global Imperative for Sustainable Cooling

The global demand for cooling is escalating rapidly, driven by urbanization, population growth, and the undeniable impact of rising global temperatures. This escalating need presents a critical energy and environmental challenge. Currently, the cooling sector accounts for approximately 20% of global building electricity use (IEA, 2020), placing immense strain on electrical grids, particularly during peak demand hours. The IEA's analysis shows that temperature-related effects were responsible for about 20% of the growth in both natural gas and electricity demand in a recent high-temperature year (IEA, 2020), emphasizing the direct link between climate and grid stress.

The problem is compounded by the dominant technology in the market: Vapor Compression Refrigeration Systems (VCRS). VCRS rely heavily on

electricity and historically utilized Hydrofluorocarbon (HFC) refrigerants, which possess a high Global Warming Potential (GWP)—often hundreds to thousands of times greater than that of carbon dioxide (CO₂) per unit mass (CCAC, 2020). HFCs are considered potent, short-lived climate pollutants (SLCPs), and their uncontrolled growth was projected to reach 4.0-5.3 GtCO₂eq/year by 2050 (UNEP, 2020).

The international community has responded decisively. The Kigali Amendment to the Montreal Protocol, adopted in 2016, mandates a global phase-down of HFCs by over 80% in the coming decades (UNEP, 2020). This binding commitment is projected to avoid up to 0.4 °C of global warming by 2100 (CCAC, 2020), underscoring the urgent need for energy-efficient and environmentally benign alternatives.

In this context, thermally driven cooling systems emerge as a compelling pathway to decarbonize the cooling sector. These systems, utilizing readily available low-grade heat sources (typically below 250°C), such as

solar thermal energy and industrial waste heat, effectively convert heat into a cooling effect. This process of energy conversion decouples the cooling process from peak grid electricity demand, contributing directly to energy security and climate mitigation goals.

This paper focuses on two leading thermal technologies: Absorption (AB) and Adsorption (AD) refrigeration. We provide an expanded review of their fundamental operating principles, analyze the cutting-edge material science (e.g., Metal-Organic Frameworks (MOFs), Nano fluids), detail cycle advancements (e.g., multi-effect cycles), and critically examine the persistent market barriers for both AB and AD cooling systems. This dual focus is essential as the global market for AB chillers, for example, is already projected to reach US 2.64 billion by the end of 2034 (Fact.MR, 2021), driven by industrial waste heat applications and stricter environmental regulations. Ultimately, this analysis aims to highlight the potential for these systems to achieve a sustainable and energy-efficient future for global cooling.

II. FUNDAMENTALS AND OPERATIONAL PRINCIPLES

Both technologies operate on a continuous thermal cycle, using heat input at the generator/desorber to drive the phase change and pressure differential required for cooling.

2.1. Absorption Refrigeration (AB) Cycles

The AB cycle relies on a working pair **consisting of a refrigerant and an absorbent**.

- a) **Process Overview:** Thermal energy is supplied to the Generator (G) to separate the refrigerant vapor from the dilute solution. This vapor is condensed (C) and then throttled, where it evaporates (E) in a low-pressure environment, absorbing heat and providing the cooling effect. The low-pressure vapor is then absorbed (A) by the concentrated solution, releasing the heat of absorption. The resulting dilute solution is pumped back to the generator.
- b) **Common Working Pairs:**
 - $\text{H}_2\text{O}/\text{LiBr}$: Used for air conditioning applications (cooling above 0°C) due to water's high latent heat. Requires low-temperature heat input (70°C – 150°C).
 - $\text{NH}_3/\text{H}_2\text{O}$: Used for refrigeration applications (cooling below 0°C) as ammonia is highly volatile.

2.2. Adsorption Refrigeration (AD) Cycles

The AD cycle employs a solid sorbent material and a refrigerant (adsorbate).

- a) **Process Overview:** The refrigerant vapor is adsorbed onto the porous surface of the solid sorbent in the Adsorber bed, driving the

evaporation and cooling effect. The saturated sorbent bed is then heated (regenerated) in the Desorber, releasing the high-pressure refrigerant vapor. The cycle often utilizes at least two beds operating alternately to ensure continuous cooling.

- b) **Common Working Pairs:**

- **Silica Gel/Water:** Low regeneration temperature (50°C – 90°C).
- **Activated Carbon/Methanol:** Suitable for sub-zero cooling applications.

III. CURRENT TRENDS: ENHANCING PERFORMANCE VIA CYCLE AND MATERIAL INNOVATIONS

Recent research efforts have focused heavily on maximizing the COP and reducing the system footprint.

3.1. Advanced Absorption Cycles: Multi-Effect Configurations

To overcome the low COP (typically 0.6–0.8) of single-effect AB chillers, multi-effect configurations have been developed, allowing for internal heat recovery.

- **Double-Effect:** Uses the heat rejected from the high-temperature condenser to drive a second generator at a lower pressure/temperature. This yields COP values typically between 1.1 and 1.3, requiring generator temperatures around 120°C – 160°C .
- **Triple-Effect:** Exploits the thermal energy across three distinct pressure levels, achieving the highest thermal efficiencies. Recent studies show that COP values can reach 1.7 to 1.9 (Wang et al., 2023). However, these cycles require high-grade heat ($>160^\circ\text{C}$) and face significant challenges in internal heat exchanger design complexity and component corrosion.

3.2. Breakthrough Sorbent Materials: Metal-Organic Frameworks (MOFs)

MOFs represent a paradigm shift in AD technology. These crystalline porous materials are constructed from metal ion clusters linked by organic ligands, offering unprecedented flexibility and surface area.

- a) **Key Advantages of MOFs:**

- **Ultra-High Specific Surface Area:** Up to $7,000\text{ m}^2/\text{g}$, allowing for significantly higher uptake of refrigerant vapor.
- **Tunable Pore Size:** Can be precisely engineered to match the size of the adsorbate molecule (H_2O , Methanol),

leading to sharp adsorption steps and high working capacity.

- b) **Performance Impact:** The use of pairs as if MOF-801/Water has demonstrated the capability to operate efficiently with regeneration temperatures as low as 55°C–65°C, drastically improving the utilization of low-grade solar or waste heat (Li et al., 2022). Furthermore, they offer increased Volumetric Cooling Density (VCD), addressing the size limitation of traditional AD systems.

3.3. Nano fluid Technology in Absorption Systems

To improve the inherently poor heat and mass transfer characteristics of traditional LiBr or NH3 solutions, researchers are incorporating nanoparticles (e.g., CuO, Al₂O₃, Graphene) into the base fluid, creating nanofluids (Zhu et al., 2021).

- **Mechanism:** The suspended nanoparticles act as nucleation sites, promoting the formation of vapor bubbles in the generator and accelerating the absorption process in the absorber.
- **Results:** Experimental data suggests that nanofluid absorbents can increase the absorption rate by 15% to 30%, leading to better heat recovery and potentially reducing the size of the heat exchangers.

IV. INTEGRATION STRATEGIES
WITH LOW-GRADE THERMAL
SOURCES

The primary advantage of these technologies lies in their ability to efficiently utilize thermal energy that would otherwise be wasted.

4.1. Solar Thermal Cooling

Solar cooling utilizes thermal collectors to generate the heat required for the generator/desorber.

- a) **System Design:** Requires solar collectors (flat plate, evacuated tube, or parabolic trough), the thermal chiller (AB or AD unit), and a thermal storage **tank** to ensure continuous operation, especially during non-sunlight hours.
- b) **Matching Technology to Temperature.**

4.2. Industrial Waste Heat Recovery

Waste heat, commonly available from industrial processes, data centers, and combined heat and power (CHP) plants, is a highly reliable and consistent heat source.

- a) **Efficiency Benefit:** Integrating the chiller with waste heat dramatically improves the overall Thermal Efficiency of the primary process, as the energy is essentially 'free' for the cooling unit. Systems utilizing waste heat above 150°C (e.g., from gas turbine exhaust) can fully exploit the high COP of triple-effect AB chillers.

Table 1: Comparison of Key Thermal Cooling System Performance.

Technology	Working Pair	Typical Tgen Range	COP Range	Key Advantage	Major Challenge
Single-Effect AB	H ₂ O/LiBr	70°C – 95°C	0.6 – 0.8	Simple design, uses low-grade heat.	Low COP, crystallization risk.
Triple-Effect AB	H ₂ O/LiBr	160°C – 200°C	1.5 – 1.9	Highest thermal efficiency (COP).	High CAPEX, operational complexity.
AD (Silica Gel)	Silica Gel/Water	50°C – 85°C	0.4 – 0.6	Very low Tgen, robust operation.	Low VCD, large size.
AD (MOFs)	MOF-801/H ₂ O	55°C – 70°C	0.5 – 0.8	Excellent performance at lowest Tgen, high working capacity.	High material CAPEX, long-term stability.

V. PERSISTENT CHALLENGES AND
RESEARCH GAPS

Despite significant technological advancements, several hurdles must be addressed for widespread market adoption.

5.1. Economic and Market Challenges

- a) **Initial Capital Cost (CAPEX):** The installation cost, particularly for integrated solar thermal systems (including collectors and storage), remains substantially higher—often 50% to 150% higher—than equivalent VCRS systems (Greenpeace, 2020). This economic barrier must be lowered through cost-effective material

manufacturing (especially MOFs) and simplified system designs.

- b) **Payback Period:** Due to the high CAPEX, the financial payback period is often too long without substantial government incentives or high electricity prices. Future efforts must focus on reducing the total installed cost to make the Life Cycle Cost (LCC) competitive.

5.2. Engineering and Operational Challenges

- a) **Low Volumetric Cooling Density (VCD):** Both AB and AD units are inherently larger and heavier per unit of cooling capacity compared to VCRS. This issue is particularly pronounced in AD due to the physical space required for the sorbent beds. Research is needed in:

- **Compact Heat Exchanger Design:** Developing micro-channel or plate heat exchangers for the absorber and generator to drastically reduce component size.
- b) **Material Stability and Durability:**
 - **Corrosion in AB:** The highly corrosive nature of LiBr solution requires expensive stainless steel or specialized inhibitors, adding to the system cost and complexity.
 - **Hydrothermal Stability in AD (MOFs):** The long-term performance and structural integrity of MOFs under repeated thermal cycling and moisture exposure need robust validation (Shah et al., 2020).

VI. FUTURE OUTLOOK AND RESEARCH DIRECTIONS

The trajectory of thermal cooling is irrevocably moving toward **higher performance, compactness, and integrated hybrid solutions**. Future success in this sector hinges on overcoming key manufacturing and integration bottlenecks to make these systems economically competitive and easier to deploy than conventional VCRS.

6.1. Hybrid Thermal-Electric Systems

The next generation of cooling solutions will necessarily involve hybridization, combining the synergistic strengths of both thermal and electric technologies. This approach is gaining traction across various sectors, including data centers and electric vehicles. A Hybrid Compression-Absorption (or Adsorption) Chiller exemplifies this integration:

- a) **Base vs. Peak Load:** The efficient, heat-driven Absorption (AB) or Adsorption (AD) unit would handle the base cooling load, leveraging low-cost or free solar/waste heat.
- b) **Flexibility and Efficiency:** A small electrical compressor is engaged only when required to meet peak demand, operate under part-load conditions, or achieve a necessary temperature lift. This strategic coordination (often managed by advanced control systems) offers unparalleled flexibility, extends the operational range, and significantly increases the overall system COP compared to running a pure electric system at partial loads. The integration principles driving efficiency improvements are often borrowed from Combined Cooling, Heat, and Power (CCHP) systems, which capture waste heat (typically 60%-80% of energy input) for productive applications, including driving absorption chillers.

6.2. Advanced Sorbent Manufacturing

The high-performance capabilities of MOFs and other advanced sorbents are currently offset by high production costs and complexity. Future research must aggressively focus on scaling up the synthesis of these materials and developing cost-effective, energy-efficient manufacturing processes to reduce the cost barrier.

- **Cost Reduction:** Focus must shift from complex batch synthesis (like the solvothermal method) to continuous-flow reactors or spray drying techniques. These methods are essential for producing high-quality MOFs and composite sorbents (e.g., combining MOFs with highly conductive materials like graphite or graphene) at industrial volumes and low cost.
- **Performance Enhancement:** Efforts are also needed to improve the application methods, such as thin-layer coating of MOFs directly onto heat exchanger surfaces. While challenging to scale, this approach minimizes thermal and mass transfer resistances, boosting the cooling system's performance and compactness.

6.3. System Simplification and Standardization

Market acceptance hinges on reducing installation complexity and ensuring reliability. Efforts must be channeled toward standardizing components and simplifying system integration, mirroring the maturity level achieved by VCRS.

- **Turnkey Solutions:** This includes developing turnkey solar cooling packages—pre-engineered, factory-assembled modules that include the thermal collectors, storage tank, chiller unit, and piping interface. Standardization in the small to medium capacity range allows for easier field installation, reduces project time, and lowers engineering costs.
- **Optimized Control Systems:** Standardization also requires developing optimized control systems that can autonomously manage the dynamic interaction between the solar heat source, thermal storage, and the chiller under various climatic and load conditions. These smart controls are vital for maximizing the utilization of solar or waste heat and ensuring high performance across a wide operational envelope, thus increasing consumer confidence and facilitating market uptake. The development of CEN Workshop Agreements (CWA) for characterizing hybrid heat pump modules exemplifies the move toward standardization.

VII. CONCLUSION

Absorption and Adsorption cooling technologies, empowered by readily available solar energy and industrial waste heat, are rapidly positioning themselves to become a dominant force in sustainable

climate control. This transition is being catalyzed by significant technological innovations: multi-effect Absorption cycles have dramatically pushed the boundaries of the Coefficient of Performance (COP) towards competitive levels (exceeding 1.5 in some cases), while the application of advanced materials like Metal-Organic Frameworks (MOFs) in Adsorption systems has achieved high cooling capacity at critically low operational temperatures (down to 55 °C), expanding the range of usable low-grade heat sources. While persistent challenges remain concerning high initial Capital Expenditure (CAPEX) and low Volumetric Cooling Density (VCD), targeted future research focusing on compact heat exchanger design, cost-effective material scale-up for MOFs, and the development of intelligent hybrid thermal-compression systems will be crucial for achieving widespread commercial viability. The successful, large-scale deployment of these thermal technologies is therefore central to meeting global energy efficiency mandates and achieving net-zero emissions targets for a robust, low-carbon cooling future.

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