



## REVIEW ARTICLE

# DESIGN AND PERFORMANCE EVALUATION OF SOLAR-ASSISTED ABSORPTION COOLING SYSTEMS FOR INSTITUTIONAL CAMPUSES IN THE NORTHEASTERN UNITED STATES

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## ABSTRACT

Institutional campuses across the Northeastern United States face increasing energy demand for space cooling due to expanding building footprints, rising comfort expectations, and warmer seasonal temperature patterns. Conventional vapor-compression cooling systems contribute significantly to peak electricity loads and greenhouse gas emissions, making sustainable alternatives essential for long-term energy resilience. Solar-assisted absorption cooling systems (SA-ACS) offer a promising pathway by integrating solar thermal collectors with absorption chillers to reduce dependence on grid electricity while enhancing operational efficiency. This review synthesizes research on the design principles, system configurations, component technologies, and performance characteristics of solar-assisted absorption cooling systems suited for institutional campuses such as universities, hospitals, and research complexes. Key considerations include solar resource availability in the Northeastern U.S., optimal collector types and orientations, thermal storage strategies, absorption chiller selection (e.g., LiBr-water systems), and integration with campus district energy networks. The paper further evaluates system performance metrics such as coefficient of performance (COP), solar fraction, cooling capacity, economic viability, and lifecycle environmental benefits. Challenges associated with intermittency of solar radiation, seasonal resource variability, high initial capital costs, and operational complexities are critically analyzed alongside potential solutions including hybridization with auxiliary heating sources, improved control strategies, and advanced predictive energy management. The review concludes by outlining future research directions and policy implications needed to accelerate the adoption of SA-ACS as a sustainable cooling solution for institutional infrastructure in the region.

## KEYWORDS

Solar-assisted absorption cooling, Institutional campus energy systems, Northeastern United States climate, Solar thermal integration, Sustainable cooling technologies

## 1. INTRODUCTION

## 1.1 Background on Cooling Demand in Institutional Campuses

Cooling demand in institutional campuses across the Northeastern United States has risen substantially due to expanding building footprints, increased internal heat gains, and climate-driven temperature variability. Universities, hospitals, and research complexes operate high-density indoor environments that require stringent thermal conditioning to ensure occupant well-being, equipment stability, and continuous research operations (Li and Yao, 2024). The Northeastern climate, characterized by warm and increasingly humid summers, intensifies peak cooling loads, forcing campuses to operate mechanical cooling for extended durations. The predominance of older buildings, many with limited passive cooling capabilities further amplifies energy-intensive cooling profiles (Fathi et al., 2020). Recent studies emphasize that institutional campuses are micro-cities whose energy consumption patterns differ significantly from residential or commercial sectors due to the simultaneous operation of laboratories, data centers, residential halls, and medical facilities (Ukpe et al., 2023). These thermal requirements are aggravated by sustainability

targets and net-zero commitments that compel institutions to reduce grid dependence while maintaining operational continuity. The integration of renewable energy and building-level optimization strategies has been highlighted as a critical pathway (Manuel et al., 2024). Campus infrastructure development across the United States also reflects a shift toward technology-enabled learning environments, increasing plug loads and associated heat gains (Ijiga et al., 2024). Similarly, emerging energy transitions such as the adoption of electric mobility and smart campus systems raise ambient and internal thermal loads, affecting cooling requirements (Idoko et al., 2024). Consequently, understanding cooling demand trends is essential for evaluating the suitability and performance of solar-assisted absorption cooling systems, which provide a sustainable alternative capable of reducing peak electricity consumption while improving energy resilience on institutional campuses.

## 1.2 Limitations of Conventional Vapor-Compression Cooling

Conventional vapor-compression cooling dominates institutional campuses, yet it presents significant technical, environmental, and economic limitations. These systems rely heavily on electricity

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consumption, generating peak-load stress on regional grids, particularly during heatwaves a challenge well documented in institutional energy resilience studies (Li et al., 2022). Vapor-compression cycles also depend on high-GWP refrigerants, contributing to environmental degradation through both direct emissions and lifecycle impacts associated with refrigeration leaks (Yildirim et al., 2023). The Northeastern U.S., characterized by aging electrical infrastructure, is particularly vulnerable to such load intensification, increasing the likelihood of outages and system failures (Okeke et al., 2024).

Institutional campuses frequently operate sensitive research and healthcare environments where cooling system reliability is non-negotiable. However, compressor-driven cooling systems exhibit high mechanical wear, requiring extensive maintenance and posing risks of operational downtime (Enyejo et al., 2024). Their performance diminishes under extreme ambient conditions, resulting in lower coefficient of performance (COP) and elevated operating costs. The tightly coupled nature of vapor-compression systems to electricity grids also exposes institutions to price volatility and demand-charge penalties, a growing financial concern for large campuses.

As digitalization accelerates, campuses integrate high-density electronics, intensifying cooling requirements beyond the design capacity of legacy systems (Ayoola et al., 2024). This mismatch exacerbates inefficiencies and elevates carbon footprints. These constraints highlight the need for alternative low-electricity cooling technologies capable of reducing mechanical complexity, mitigating refrigerant risks, and stabilizing long-term energy expenditures. Solar-assisted absorption cooling systems emerge as a strong candidate due to their lower electrical dependence, thermally driven cycles, and superior integration potential with renewable energy sources.

### 1.3 Emergence of Solar-Assisted Absorption Cooling Systems

The growing interest in solar-assisted absorption cooling systems (SA-ACS) reflects an urgent need to address the limitations of electricity-intensive vapor-compression technologies on institutional campuses. Absorption systems operate on thermally driven cycles most commonly lithium-bromide/water configurations that leverage low-grade heat rather than mechanical compression, allowing solar thermal energy to serve as the primary driving source (Chen, et al., 2023). This shift enables campuses to decouple cooling from electricity consumption, thereby reducing peak-load stress and enhancing energy resilience. In addition, integration of thermal energy storage enables smoothing of solar intermittency and supports continuous cooling during cloudy periods or evening hours (Ko and Chua, 2022).

Recent advances in renewable energy integration have strengthened the feasibility of SA-ACS. The broader energy transition toward sustainable thermal systems has propelled institutions to adopt hybrid solar heating-cooling infrastructures aligned with decarbonization goals (Godwins et al., 2024). Concurrently, digitalization particularly through predictive analytics and digital twin frameworks supports optimized operation, enabling real-time performance tracking and fault prediction, which improve system efficiency and reliability (Okeke, et al., 2024).

Renewable-energy-enhanced cooling aligns with campus sustainability models that promote circular energy flows and reduced carbon emissions. The increasing synergy between AI-enabled energy forecasting and solar-thermal generation further accelerates adoption by improving load matching and minimizing operational uncertainty (Idoko et al., 2024). For Northeastern U.S. campuses, where peak electricity prices and aging infrastructure pose financial and operational challenges, SA-ACS offers a resilient, low-carbon alternative that aligns with institutional climate action strategies while ensuring stable, reliable cooling performance.

### 1.4 Study Objectives and Scope

This review aims to critically examine the design principles, operational characteristics, and performance metrics of solar-assisted absorption cooling systems (SA-ACS) tailored for institutional campuses in the Northeastern United States, where climatic conditions, infrastructure age, and energy-use patterns present unique engineering and sustainability challenges. The objectives are fourfold: first, to analyze the thermal and environmental factors influencing cooling demand in campus environments; second, to evaluate the technological limitations of conventional vapor-compression cooling systems and identify gaps that SA-ACS can address; third, to synthesize existing research on solar thermal integration, absorption chiller technologies, and hybridized energy architectures applicable to institutional infrastructures; and fourth, to assess performance indicators such as coefficient of performance (COP),

solar fraction, operational resilience, and lifecycle environmental impacts. The scope of this study spans solar resource availability, system design configurations, thermal storage integration, and feasibility considerations that influence deployment across academic, medical, and research-based campus settings. By establishing this structured analytical framework, the review provides a comprehensive foundation for understanding how SA-ACS can contribute to decarbonization initiatives, energy resilience strategies, and long-term operational efficiencies within the context of regional climate realities and institutional sustainability goals.

### 1.5 Structure of the Review

This review is organized into six major sections to provide a coherent and methodical exploration of solar-assisted absorption cooling systems for institutional campuses in the Northeastern United States. Following the introduction, Section 2 examines the climatic conditions and solar resource availability in the region, highlighting their implications for system performance. Section 3 presents the technical architecture of SA-ACS, including absorption cycle mechanics, solar collector technologies, thermal storage, and control strategies. Section 4 analyzes design considerations for campus-level deployment, focusing on load profiling, district energy integration, economic feasibility, and structural constraints. Section 5 evaluates system performance through simulation studies, empirical case analyses, and lifecycle assessments. Finally, Section 6 addresses the technical, economic, and policy challenges that influence SA-ACS adoption, offering insights into future research directions and the broader potential of solar-driven cooling technologies in institutional sustainability frameworks.

## 2. SOLAR RESOURCE AND CLIMATIC CONDITIONS IN THE NORTHEASTERN UNITED STATES

### 2.1 Solar Irradiation Characteristics and Seasonal Variability

Solar irradiation in the Northeastern United States demonstrates substantial diurnal and seasonal fluctuations that directly influence the feasibility and performance stability of solar-assisted absorption cooling systems. The region experiences peak irradiation during late spring and summer, with average daily global horizontal irradiance ranging between 4.0–5.5 kWh/m<sup>2</sup>, while winter months show reductions of more than 50% due to shorter daylight duration, cloud cover, and low solar angles (Habe et al., 2020) as shown in figure 1. These seasonal disparities create a temporal mismatch between cooling demand, highest in summer and solar availability, which necessitates advanced thermal storage and hybrid operational strategies to maintain system reliability (Perez et al., 2020). Multiple studies highlight the importance of high-resolution solar resource forecasting for optimizing system control in dynamic climates. Data-driven modeling frameworks, increasingly applied in energy system planning, enhance prediction accuracy and support real-time system optimization (Enyejo et al., 2024). The integration of IoT-enabled sensing platforms further strengthens the ability to capture irradiation patterns and microclimatic variations at the campus scale (Idoko et al., 2024). Thermal performance considerations are also linked to heat-transfer efficiency and collector operating ranges. Research on hydrogen fuel cell thermal optimization demonstrates how thermodynamic modeling approaches can be adapted to solar-thermal system evaluation, especially under fluctuating heat loads (Aikins et al., 2024). Broader renewable energy assessments show that the Northeastern region's moderate but stable summer irradiation is sufficient to drive absorption systems when appropriately sized and supported by auxiliary thermal inputs (Bashiru et al., 2024). Understanding these nuanced irradiation dynamics is therefore central to designing resilient, climate-aligned solar-assisted cooling systems for institutional campuses.



**Figure 1:** Picture of Solar panels capturing direct and diffuse sunlight, highlighting seasonal variability influencing solar-assisted cooling efficiency (Vickerman, J. 2024).

Figure 1 shows a large array of photovoltaic solar panels angled toward the sun, with strong direct beam radiation striking the surface under a mostly clear sky featuring scattered cumulus clouds. This visual context illustrates the fundamental dynamics discussed in *Section 2.1: Solar Irradiation Characteristics and Seasonal Variability*, where solar availability is influenced by atmospheric clarity, solar elevation, and seasonal shifts. The bright, low-angle sunlight in the image suggests either early morning or late afternoon conditions periods characterized by higher diffuse radiation components and longer optical air mass, which reduce instantaneous irradiance compared to midday peaks. The panels' orientation and reflective glint highlight their role in maximizing incident solar energy, yet the presence of moving cloud formations reflects the intermittency challenges typical of mid-latitude climates like the Northeastern United States. During summer months, such conditions support strong solar gains essential for driving solar-assisted absorption cooling systems, while winter seasons exhibit lower solar altitude, increased cloud cover, and shorter photoperiods, substantially reducing available thermal input. The image therefore visually encapsulates the interplay between direct, diffuse, and reflected solar components, demonstrating how weather variability, atmospheric scattering, and seasonal sun-path geometry collectively shape the temporal performance profile of solar-thermal systems used in institutional campus cooling applications.

## 2.2 Temperature and Humidity Profiles Influencing Cooling Demand

The Northeastern United States exhibits warm, humid summers that significantly elevate cooling loads in institutional campuses. High relative humidity, often exceeding 70% in peak months, reduces latent heat removal efficiency and intensifies mechanical cooling requirements (Yang 2021). At the same time, rising regional temperatures attributed to climate variability amplify sensible cooling loads, particularly in dense academic settings where internal gains from electronics, occupancy, and laboratory processes persist throughout the day (Meng et al., 2023). These combined thermal and moisture conditions create complex cooling profiles that absorption-based systems must accommodate through appropriate cycle configurations and control strategies. Studies addressing winter climatic stresses emphasize that extreme weather patterns influence building envelope performance, altering year-round thermal balances and indirectly affecting sizing considerations for cooling systems (Ijiga et al., 2024). Environmental monitoring research further highlights the importance of integrating meteorological and microclimatic datasets for precise load forecasting, allowing institutions to anticipate humidity-induced cooling spikes (Idoko et al., 2024). IoT-enabled sensor networks provide real-time localized thermal and humidity measurements that support adaptive cooling strategies and predictive system control (Ayoola et al., 2024).

Advanced analytical tools, such as machine learning-driven thermal modeling applied in environmental research, enhance understanding of heat-moisture interactions and their operational implications for solar-thermal systems (Okpanachi et al., 2025). Such insights strengthen the ability to design absorption cooling systems that maintain stable evaporator temperatures despite fluctuating dew points. Overall, temperature-humidity interactions in the Northeast underscore the need for cooling technologies capable of managing high latent loads while integrating efficiently with region-specific climatic patterns.

## 2.3 Implications for Solar Thermal System Design

Designing solar thermal systems for absorption cooling in the Northeastern United States requires meticulous consideration of irradiance variability, collector efficiency behavior, and thermal-storage coupling. Solar thermal collector performance is highly sensitive to ambient temperature, incidence angle modifications, and diffuse radiation components, all of which characterize mid-latitude climates (Duffie et al., 2020). Seasonal variability creates design challenges related to stagnation temperatures, heat-transfer fluid selection, and oversized arrays, necessitating precise thermal modeling and dynamic control strategies (García-Menéndez et al., 2022).

Thermal property characterization, extensively studied in material-performance research, informs decisions regarding absorber plate coatings, insulation layers, and corrosion-resistant components when designing long-lived solar infrastructure (Idoko et al., 2024). The application of AI-supported risk assessment models strengthens system reliability by identifying performance anomalies and thermal degradation trends before critical failures occur (Ogbuonyalu et al., 2025). Remote sensing techniques enable high-resolution mapping of rooftop irradiance patterns and shading dynamics, ensuring accurate collector placement and orientation on institutional buildings (Adegbola et al., 2025).

Subsurface and geochemical modeling approaches, though traditionally applied in geological contexts, offer valuable analogues for studying thermal gradient behavior and optimizing heat-exchanger interfaces in absorption systems (Eguague et al., 2025). These multidisciplinary insights converge to support solar thermal system architectures capable of compensating for Northeastern climatic fluctuations while sustaining the high-temperature outputs required to drive lithium-bromide absorption chillers (Smith, 2025). Ultimately, robust solar thermal design must integrate material science, predictive analytics, and environmental monitoring to ensure operational efficiency and year-round system resilience.

## 2.4 Comparison with Other U.S. Climatic Zones

The Northeastern United States differs markedly from other U.S. climatic zones in solar resource intensity, temperature variability, and humidity profiles, all of which influence the suitability and performance of solar-assisted absorption cooling systems. Compared to the Southwest, where annual irradiation exceeds 6.5 kWh/m<sup>2</sup>/day, the Northeast receives significantly lower and more diffuse solar energy, necessitating larger collector areas and higher-efficiency absorber designs (Brown et al., 2016) as shown in table 1. Similarly, Southern states experience prolonged high-temperature seasons with lower humidity variability, enabling more predictable cooling loads relative to the humidity-driven latent loads dominating Northeastern campuses (Li, 2012).

Regional environmental studies show that climatic stressors vary widely across the country, shaping operational risks and influencing system resilience strategies (Ayoola et al., 2024). Technology adaptation research confirms that optimization approaches must be climate-specific, as cooling technologies successful in arid or semi-arid environments cannot be deployed without modification in humid, cloud-prone regions (Enyejo et al., 2024). Environmental analytics further reveal that occupational and building-use patterns differ between regions, adding additional layers of complexity to cooling system design (Idoko et al., 2024).

Edge AI technologies offer new opportunities for real-time climate-responsive cooling adjustments, particularly valuable in the Northeast where conditions fluctuate rapidly (Uzoma et al., 2024). Such adaptive frameworks are less critical in regions with stable climatic profiles. These comparisons underscore the need for regionally calibrated solar-assisted absorption cooling designs that account for solar intermittency, latent-dominant cooling loads, and variable ambient conditions unique to the Northeastern U.S.

**Table 1: Summary of Comparison with Other U.S. Climatic Zones**

Focus Area	Key Technical Points	Implications for Northeastern U.S.	Design/Operational Considerations
Solar Resource Variability	Southwest and Mountain regions have high direct-normal irradiation; Southeast has high diffuse solar; Midwest exhibits moderate variability.	Northeast receives lower winter irradiance and higher diffuse radiation, reducing collector efficiency.	Larger collector areas, steeper tilt angles, and high-efficiency evacuated-tube collectors are required.
Cooling Load Distribution	Sunbelt states experience prolonged cooling seasons; Northern regions have shorter but humidity-intense cooling seasons.	Northeast cooling loads spike during humid summer months, driven by latent heat loads.	Systems must be designed for higher dehumidification demand and peak-load matching.

Table 1 (Cont): Summary of Comparison with Other U.S. Climatic Zones			
Focus Area	Key Technical Points	Implications for Northeastern U.S.	Design/Operational Considerations
Climate Sensitivity	Arid climates promote stable solar output; coastal climates introduce rapid weather changes.	Frequent cloud cover and temperature swings complicate generator temperature control.	Incorporation of thermal energy storage and advanced control algorithms.
Performance Reliability	Regions like Arizona exhibit stable COP due to consistent solar availability.	COP in the Northeast fluctuates seasonally and diurnally.	Hybridization with auxiliary heat sources becomes essential for reliability.

### 3. SYSTEM ARCHITECTURE OF SOLAR-ASSISTED ABSORPTION COOLING SYSTEMS

#### 3.1 Overview of Absorption Cooling Principles (LiBr-Water, Ammonia-Water)

Absorption cooling systems rely on thermally activated refrigeration cycles that substitute mechanical compression with chemical absorption, making them ideal for integration with solar thermal energy. The LiBr-water cycle operates using water as the refrigerant and lithium bromide as the absorbent, functioning under sub-atmospheric pressures to produce chilled water with high thermodynamic efficiency (Jin et al., 2020). Conversely, ammonia-water systems utilize ammonia as the refrigerant, enabling lower evaporator temperatures suitable for applications requiring sub-zero cooling (Liu et al., 2018). The performance of both systems is influenced by solution concentration, heat-transfer coefficients, and generator temperatures, with solar-driven systems requiring generator temperatures between 70–95°C for LiBr-water and above 120°C for ammonia-water cycles.

Thermodynamic behavior in these systems aligns with chemical energetics research, emphasizing enthalpic interactions and mass-transfer dynamics that govern absorber-generator equilibrium. Advances in heat transfer modeling provide deeper insight into solution flow stability, crystallization limits, and absorber surface behavior under variable climatic loads. Material thermophysical property studies further inform corrosion-resistant component selection, critical due to the hygroscopic and corrosive nature of LiBr solutions (Idoko et al., 2024). Optimization frameworks integrating fluid energy interactions contribute to improved coefficient of performance (COP), reduced exergy loss, and more responsive control of thermal gradients across the cycle (Enyejo et al., 2024).

By understanding these foundational principles, solar-assisted absorption cooling systems can be engineered to operate reliably under Northeastern U.S. climatic conditions, ensuring stable cooling outputs despite irradiation variability and humidity-driven cooling load fluctuations.

#### 3.2 Solar Thermal Collector Options and Design Considerations

Solar-assisted absorption cooling performance depends significantly on the selection, design, and configuration of solar thermal collectors. Flat-plate collectors, though cost-effective, operate efficiently only at moderate temperature levels, making them suitable for LiBr-water systems requiring 70–95°C generator temperatures (Kadam et al., 2025) as shown in figure 2. Evacuated tube collectors (ETCs), by contrast, exhibit superior thermal retention and reduced convective losses, enabling stable output under diffuse radiation and colder ambient conditions characteristics typical of the Northeastern U.S. (Greco et al., 2020). Their ability to achieve temperatures above 120°C also supports ammonia water cycles.

Geothermal and thermal flux modeling frameworks provide valuable analogues for predicting collector heat-transfer dynamics and optimizing absorber design under fluctuating solar intensities (Eguague et al., 2025).

High-efficiency heat exchanger optimization research reinforces the importance of material selection, fin geometry, and fluid circulation rates to minimize exergy loss and ensure consistent collector efficiency. Climate energy system interaction studies strengthen understanding of how local irradiance patterns influence collector tilt angles, orientation, and array spacing. Advanced computational thermal analysis supports predictive modeling of stagnation temperatures, absorber plate stresses, and fluid stability under rapid irradiance transitions (Ayoola et al., 2024). These insights inform critical design decisions such as anti-crystallization protocols for LiBr systems, frost mitigation for ammonia-water cycles, and selective coating specifications that maximize absorptivity while minimizing emissivity (Smith, 2025). Overall, solar collector design must respond to regional climatic variability while meeting the thermodynamic requirements of the absorption cycle to ensure year-round operational reliability.

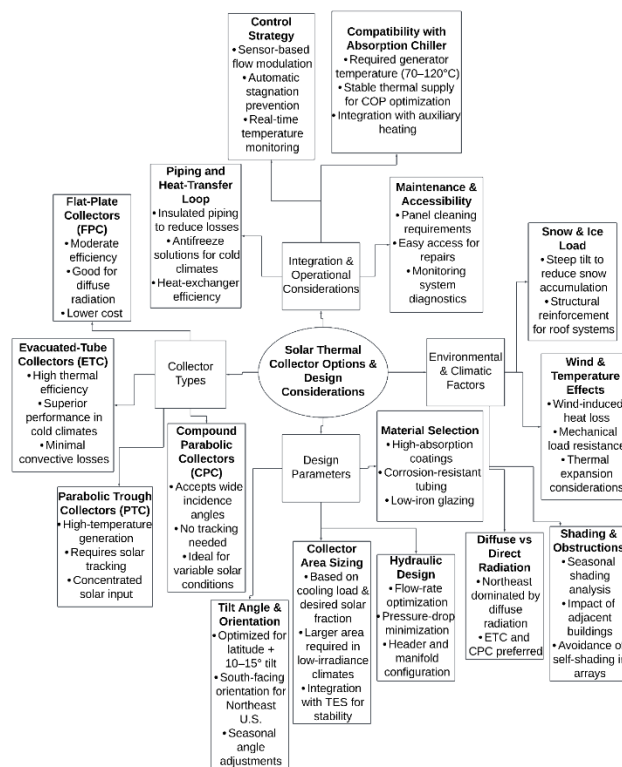


Figure 2: Hierarchical design framework summarizing solar thermal collector options and key engineering considerations for solar-assisted absorption cooling systems.

The diagram illustrates the full spectrum of design considerations for solar thermal collectors used in solar-assisted absorption cooling systems, beginning with a central node representing “Solar Thermal Collector Options and Design Considerations” and branching into four major technical domains. The first branch, *Collector Types*, outlines the primary technologies—flat-plate, evacuated-tube, parabolic trough, and compound parabolic collectors—highlighting their efficiency characteristics, temperature capabilities, and suitability for varying solar conditions. The second branch, *Design Parameters*, encompasses engineering decisions such as optimal tilt angle, south-facing orientation for the Northeastern U.S., collector-area sizing based on target solar fraction, hydraulic flow optimization, and selection of thermally efficient, corrosion-resistant materials.

The third branch, *Environmental & Climatic Factors*, captures external influences such as the dominance of diffuse radiation in the Northeast, shading from surrounding buildings, wind-driven thermal losses, and snow-load considerations that affect structural design and overall collector performance. The fourth branch, *Integration & Operational Considerations*, covers the practical elements of embedding collectors within a functioning cooling system, including insulated piping layouts, heat-transfer fluid selection, advanced control strategies to prevent stagnation, and matching collector output to the generator temperature requirements of absorption chillers. Collectively, the diagram demonstrates how solar collector selection and design must balance climatic constraints, system performance requirements, and architectural limitations to ensure reliable and efficient cooling operations across

institutional campuses in the Northeastern United States.

### 3.3 Thermal Energy Storage Integration

Thermal energy storage (TES) is essential for mitigating solar intermittency and stabilizing absorption cooling operation in climates with fluctuating irradiance. Both sensible and latent heat storage systems are employed to buffer thermal input, with water-based sensible storage commonly paired with LiBr–water systems due to compatibility, low cost, and ease of integration (Alva et al., 2017). Latent heat storage using phase-change materials (PCMs) offers higher energy density and more stable discharge profiles, enabling smoother generator temperature control during cloudy intervals (Boretti, 2025).

Energy buffering principles explored in complex thermal systems research provide valuable insights into maintaining thermal field stability under dynamic operating conditions (Ijiga, et al., 2024). Predictive control strategies enhance TES responsiveness, enabling real-time modulation of charge and discharge cycles to maintain generator temperature thresholds essential for absorption cycle continuity (Ilesanmi et al., 2024). Environmental heat–mass transfer studies highlight the importance of designing TES with adequate mixing, stratification control, and insulation to preserve exergy and minimize parasitic losses (Aikins et al., 2025).

Distributed energy storage optimization research further underscores the role of TES in hybrid solar–thermal architectures, particularly in coordinating solar thermal production with auxiliary heat sources and variable cooling loads (Adewoye and Ugochukwu, 2024). Integrating TES with solar-assisted cooling not only enhances operational resilience but also improves system COP, reduces auxiliary fuel consumption, and extends the operational window for solar-driven absorption cycles in the Northeastern U.S.

### 3.4 Hybridization with Auxiliary Heat Sources

Hybridization is a critical design strategy for ensuring continuous absorption cooling operation when solar irradiance is insufficient. Auxiliary heat sources including natural gas boilers, biomass heaters, and electric resistance heaters are integrated to maintain generator temperatures within operational limits, particularly during early morning periods, cloudy conditions, and winter months (Siddique et al., 2022) as shown in table 2. Multi-source thermal integration allows seamless transition between solar and auxiliary heating, improving system reliability and reducing thermal cycling stress on the absorber and generator (Bordignon, 2022).

Hybrid renewable system modeling demonstrates that optimized dispatch strategies can significantly reduce auxiliary fuel consumption while ensuring uninterrupted cooling loads (Ayoola et al., 2024). Thermal load balancing research further highlights the importance of coordinated control between solar collectors, TES units, and auxiliary heat exchangers to prevent temperature overshoot and maintain stability across the generator loop (Manuel et al., 2024). Combustion-based auxiliary heating studies provide insight into optimizing burner efficiency, minimizing emissions, and ensuring rapid thermal response to fluctuating cooling demands.

Fuel-flexible heating systems are increasingly relevant for institutional campuses transitioning toward decarbonization, enabling the incorporation of biogas, hydrogen blends, or other low-carbon fuels to support auxiliary heating without compromising sustainability commitments (Avevor et al., 2025). Effective hybridization enhances system COP, mitigates intermittency challenges, and ensures the operational resilience necessary for Northeastern climatic conditions.

Table 2: Summary of Hybridization with Auxiliary Heat Sources			
Focus Area	Key Technical Points	Implications for Northeastern U.S.	Design/Operational Considerations
Need for Hybridization	Solar availability varies; auxiliary heat stabilizes generator temperature.	Northeast's winter irradiance limitations necessitate supplemental heating.	Natural-gas boilers, electric heaters, or waste heat streams can be integrated.

Table 2 (Cont): Summary of Hybridization with Auxiliary Heat Sources			
Focus Area	Key Technical Points	Implications for Northeastern U.S.	Design/Operational Considerations
Reliability Enhancement	Auxiliary systems prevent crystallization and low-temperature cycle failure.	Mitigates risks associated with overcast periods and rapid temperature drops.	Controls must balance solar and auxiliary input to maintain efficient COP.
Seasonal Operation	Auxiliary heat may dominate during winter but remain minimal in summer.	Reduces operational downtime, ensuring year-round system functionality.	Seasonal switching logic and predictive control scheduling are critical.
Energy Optimization	Hybrid systems reduce oversizing of solar collectors.	Enables economically feasible system sizing for institutional campuses.	Optimal sizing of auxiliary units minimizes fuel consumption and emissions.

### 3.5 Control, Monitoring, and Operational Strategies

Effective control and monitoring strategies are essential for optimizing the performance of solar-assisted absorption cooling systems operating under variable climatic and load conditions. Advanced control frameworks combine predictive algorithms, real-time environmental sensing, and adaptive operating rules to maintain generator temperatures, prevent crystallization, and ensure stable cooling outputs (Li and Zhang, 2020). Intelligent monitoring architectures integrate distributed sensor networks, cloud-based analytics, and fault-detection modules to support early anomaly identification and continuous performance optimization (Xu et al., 2023).

IoT-enabled thermal monitoring systems enhance situational awareness by providing high-resolution temperature, humidity, and irradiance data across collector fields, generator loops, and TES units (Ayoola et al., 2024). Predictive reliability optimization frameworks strengthen operational resilience by anticipating system failures and recommending pre-emptive interventions (Enyejo et al., 2024). AI-based decision support tools refine cycle-level modulation including solution pump speed, generator heating rate, and evaporator load matching resulting in improved COP and reduced exergy destruction (Ocharo, et al., 2023).

Real-time control of environmental systems supports dynamic adaptation to rapid changes in weather conditions, allowing absorption chillers to respond efficiently to shifts in solar availability and cooling demand (Avevor, et al., 2025). These strategies collectively ensure that system operation remains robust, safe, and energy-efficient, particularly in the Northeastern United States where climatic variability demands precise, responsive, and intelligent control.

## 4. DESIGN CONSIDERATIONS FOR INSTITUTIONAL CAMPUS DEPLOYMENT

### 4.1 Load Assessment and Cooling Demand Profiles

Accurate load assessment is foundational to designing solar-assisted absorption cooling systems for institutional campuses in the Northeastern United States, where climatic variability and complex occupancy patterns shape cooling demand. Educational, research, and medical buildings exhibit high internal heat gains from laboratory equipment, ventilation requirements, and dense occupancy patterns, leading to pronounced afternoon peak loads (Fathi et al., 2021) as shown in table 3. Seasonal cooling fluctuations are further intensified by humid summers in the Northeast, which elevate latent load components and require cooling systems capable of delivering substantial dehumidification (O'Kelly et al., 2014). Energy performance modeling for institutional infrastructures highlights the influence of internal thermal behavior, plug-load density, and ventilation schedules in determining hourly cooling demand profiles (Ijiga et al., 2024).

Predictive analytics frameworks have demonstrated exceptional capability in forecasting cooling loads by integrating historical weather patterns, occupancy trends, and environmental sensor data (Ilesanmi et al., 2024). This level of analytical precision is crucial for absorption cooling systems whose performance is highly sensitive to generator temperature thresholds and load-matching accuracy. Environmental thermal behavior studies reveal that humid climates drive non-linear load escalations that absorption systems must accommodate through dynamic cycle modulation (Ocharo et al., 2024).

Climate energy interaction research shows that Northeastern campuses experience significant load diversity arising from mixed building typologies, requiring integrated load assessment models that account for cross-building heat flows, district energy interactions, and variable solar availability (Smith, 2025). Therefore, comprehensive cooling load profiling enables optimal system sizing, improved COP performance, and reliable design of solar-assisted absorption systems under region-specific thermal demands.

**Table 3: Summary of Load Assessment and Cooling Demand Profiles**

Focus Area	Key Technical Points	Implications for Northeastern U.S.	Design/Operational Considerations
Internal Heat Gains	Labs, classrooms, medical spaces produce significant heat from equipment and occupancy.	Peak loads occur midday to late afternoon, aligned with moderate solar availability.	Load profiling tools must incorporate occupancy patterns and equipment intensity.
Latent vs. Sensible Load	Northeast humidity increases latent cooling requirements.	Higher absorber throughput is required to handle moisture removal.	Cooling systems must incorporate dehumidification-capable design parameters.
Seasonal Load Variability	Summer peaks dominate; spring and fall remain variable.	Absorption systems must accommodate fluctuating generator demands.	TES supports smoother transitions and peak-load management.
Predictive Modeling	AI-based load forecasting improves accuracy.	Reduces mismatch between cooling output and real-time demand.	Integration with campus energy management systems improves reliability.

#### 4.2 Integration with Existing Campus District Energy Systems

Integrating solar-assisted absorption cooling systems into existing district energy networks requires sophisticated thermal coordination strategies capable of managing heat flows, load diversity, and varying supply temperatures. District cooling systems in institutional campuses often operate centralized chilled-water loops that distribute cooling across academic, residential, and research buildings, requiring stable and predictable output from integrated absorption chillers (Cao and Hasan, 2021). Solar-driven absorption units must therefore synchronize generator temperature cycles with district return-loop conditions to avoid hydraulic instability and thermal imbalance (Smaisim et al., 2023). Studies on district energy behavior under dynamic cooling loads reveal that temperature stratification, flow-rate modulation, and loop pressure dynamics directly influence the absorption chiller's ability to maintain consistent COP values (Ijiga et al., 2024).

Smart-grid-enabled thermal coordination enables predictive dispatch of cooling production based on real-time demand forecasting, solar availability, and TES charging state (Ilesanmi et al., 2024). Multi-node thermal balance analyses further demonstrate that improper integration may lead to thermal lag, reverse flow events, or insufficient cooling distribution in peak-load buildings (Ocharo et al., 2024). Distributed energy synchronization research indicates that hybrid campus environments where medical centers, data centers, and laboratories

operate simultaneously require highly responsive control strategies to prevent bottlenecks in chilled-water distribution (Idoko, et al., 2024). Effective integration must therefore include variable-speed pumping, pressure-independent control valves, and strategically positioned thermal buffers (Griffith and Ellis, 2004). A well-designed integration framework enables solar-assisted absorption cooling systems to supplement district cooling loops while reducing peak grid loads and enhancing system resilience.

#### 4.3 Collector Sizing, Orientation, and Placement Constraints

Collector sizing and placement constitute critical design steps for ensuring adequate thermal energy supply to drive absorption cooling cycles. Solar-cooling applications typically require large collector areas, with sizing determined by cooling load profiles, TES capacity, and acceptable solar fraction (Khan et al., 2025). Northeastern U.S. climates demand larger collector arrays due to lower winter irradiation and higher diffuse radiation fractions, requiring precise tilt and azimuth optimization to maximize seasonal yield (Rudianto, 2025). Environmental constraint analyses highlight the importance of accounting for shading from nearby buildings, vegetative cover, and rooftop equipment, which can significantly impair collector field efficiency (Avevor et al., 2025).

Computational optimization research demonstrates that algorithm-driven placement strategies can enhance solar accessibility by evaluating shading patterns, solar paths, and roof structural loads simultaneously. Urban microclimate studies reveal that wind patterns, heat-island effects, and localized temperature variations alter collector thermal performance, requiring region-specific correction factors (Ocharo et al., 2024). Structural assessment research additionally emphasizes load-bearing constraints, vibration considerations, and penetrations required for piping infrastructure, which influence collector placement feasibility on older institutional buildings.

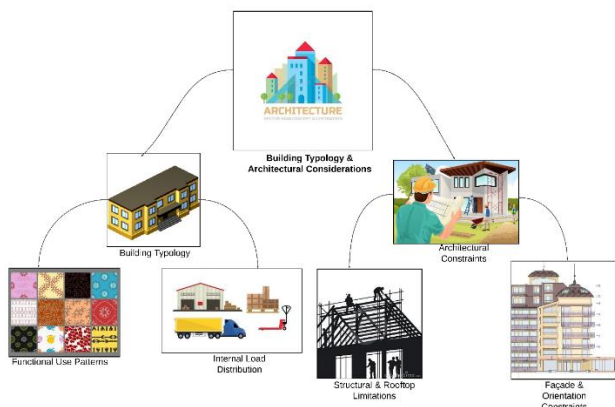
Proper collector field design must therefore integrate environmental modeling, structural constraints, and thermodynamic requirements to ensure consistent generator temperature support (Ko and Chua, 2022). In solar-assisted absorption cooling systems, misalignment or undersizing directly compromises COP performance and may require excessive auxiliary heating, reducing system sustainability. Optimized collector placement enables efficient heat capture while accommodating architectural and climatic limitations.

#### 4.4 Building Typology and Architectural Considerations

Building typology exerts strong influence on solar-assisted absorption cooling system performance due to variations in envelope composition, internal load density, ventilation requirements, and occupancy schedules. Educational buildings typically experience intermittent occupancy with sharp afternoon cooling peaks, while laboratories and medical facilities maintain continuous operation with high internal heat gains, necessitating cooling systems capable of sustained thermal output as shown in figure 3 (Perez et al., 2018). Architectural constraints such as façade orientation, glazing ratios, and roof geometry further determine the feasibility of collector placement and piping integration (Gang et al., 2016). Heat-flow interaction studies underline that building envelope performance significantly affects cooling loads, influencing generator temperature demands and system sizing (Ijiga et al., 2024). Energy-flow modeling of institutional structures demonstrates that thermal zoning, envelope insulation levels, and ventilation strategies must be integrated into overall system design to achieve stable COP values (Ilesanmi et al., 2023). Research on occupant-driven cooling patterns reveals that behavioral factors such as manual thermostat adjustments and varying internal heat-gain patterns must be incorporated into predictive cooling models to avoid underperformance or oversizing (Ocharo et al., 2024). Structural compatibility assessments indicate that older university buildings often have limited roof load capacity, restrictive mechanical spaces, and constrained retrofitting pathways, necessitating hybrid rooftop-ground installation strategies for solar collectors (Agaba et al., 2024). Given these constraints, building typology must be central to system design, influencing collector placement, system sizing, distribution routing, and operational strategies across campus environments.

Figure 3 provides a structured overview of the key building-typology and architectural factors that influence the feasibility and performance of solar-assisted absorption cooling systems on institutional campuses. At the center is the concept of *Building Typology and Architectural Considerations*, from which two major branches extend. The first branch, *Building Typology*, captures how different functional uses shape cooling demand: laboratories with continuous equipment-driven heat loads and stringent ventilation requirements, classrooms with intermittent

occupancy and pronounced afternoon peaks, medical facilities with energy-dense equipment and high air-change rates, and office buildings with more stable but moderate internal loads.



**Figure 3:** Diagram illustrating how building typology and architectural constraints influence the design and integration of solar-assisted absorption cooling systems.

These distinctions highlight how occupant behavior, operational schedules, and internal heat-gain intensities must be incorporated into the system's thermal design. The second branch, *Architectural Constraints*, addresses the physical and structural barriers that influence collector placement and system integration. Structural and rooftop constraints include limited roof load capacity especially in older buildings and restricted mechanical room space for absorbers, pumps, and piping. Façade and orientation constraints cover shading from adjacent campus structures, roof geometry issues such as limited south-facing surfaces, and suboptimal tilt angles that reduce solar exposure. Together, the diagram demonstrates that effective system design depends not only on thermal engineering but also on a detailed understanding of how building types, use patterns, structural limitations, and physical orientation interact to determine the practicality and performance of solar thermal installations in Northeastern U.S. institutional settings.

#### 4.5 Economic and Technical Feasibility Assessment

Evaluating the feasibility of solar-assisted absorption cooling systems requires careful assessment of both capital investment and operational performance. Techno-economic analyses confirm that collector field cost, absorption chiller capacity, thermal storage integration, and auxiliary heater requirements constitute the largest components of system expenditure (Sadi et al., 2021). Northeastern campuses, where solar resource availability is moderate, must account for larger collector areas and more robust control systems, which increase initial costs but enable significant reductions in peak electricity demand and long-term operational expenses (Li and Ma, 2023). Lifecycle cost modeling demonstrates that system feasibility improves substantially when integrated into broader campus energy strategies, where shared thermal loops, centralized plant retrofits, and coordinated district-energy controls reduce redundancy and optimize utilization (Idoko et al., 2024). Performance benchmarking frameworks highlight the importance of aligning COP performance, solar fraction, and thermal-storage discharge efficiency with established energy-savings targets to ensure favorable payback periods (Ilesanmi et al., 2024). Risk assessment studies show that uncertainties related to climatic variability, solar degradation, and auxiliary fuel costs must be considered through probabilistic modeling to avoid underestimating long-term financial exposures (Ocharo, 2024). Financial feasibility research emphasizes that grant incentives, decarbonization mandates, and renewable-energy tax structures significantly improve system viability for institutional campuses. When appropriately optimized, solar-assisted absorption cooling systems deliver competitive lifecycle performance, reduced carbon emissions, and enhanced operational resilience, supporting institutional sustainability objectives within the Northeastern United States.

## 5. PERFORMANCE EVALUATION AND CASE STUDIES

### 5.1 Performance Metrics: COP, Solar Fraction, and Energy Savings

Performance evaluation of solar-assisted absorption cooling systems relies heavily on three core indicators: coefficient of performance (COP), solar fraction, and energy-savings potential. COP quantifies the thermal efficiency of the absorption cycle by measuring cooling output relative to

heat input, making it sensitive to generator temperature stability and solution concentration (Chen et al., 2022) as shown in table 4. Solar fraction, the proportion of thermal energy supplied by solar collectors serves as a critical sustainability measure and is highly dependent on irradiance levels, collector sizing, and thermal-storage adequacy (Liu et al., 2015). Research on thermal exchange optimization demonstrates how improved heat-transfer configurations enhance system COP by reducing exergy destruction in high-temperature generator loops (Aikins et al., 2024).

Renewable-energy performance modeling reveals that solar-assisted systems demonstrate substantial reductions in grid-electricity dependency, especially during peak summer demand when solar availability aligns with cooling loads (Bashiru et al., 2024). AI-enhanced thermodynamic modeling supports improved parameter tuning for absorber-generator operation, reducing inefficiencies associated with fluctuating climatic conditions typical of the Northeastern U.S. (Idoko et al., 2024). Computational performance analytics further underscore the importance of real-time control in stabilizing COP and maximizing thermal energy utilization (Ayoola et al., 2024). Energy-saving assessments show that campuses integrating solar-assisted absorption cooling can achieve up to 30–60% reductions in electricity-based cooling demand depending on system configuration, thermal-storage capacity, and hybridization strategies (Ayinde, et al., 2022). These metrics collectively provide a comprehensive framework for evaluating system effectiveness and guiding optimization strategies across institutional campuses.

**Table 4:** Summary of Performance Metrics: COP, Solar Fraction, and Energy Savings

Focus Area	Key Technical Points	Implications for Northeastern U.S.	Design/Operational Considerations
COP (Coefficient of Performance)	Dependent on generator temperature, absorber efficiency, and solution stability.	Lower and variable solar input reduces achievable COP.	High-efficiency collectors, insulated piping, and intelligent controls are necessary.
Solar Fraction	Indicates proportion of heat supplied by solar energy.	Lower solar fraction expected due to cloud cover and winter irradiation.	Larger collector fields and optimized tilt angles help increase solar fraction.
Energy Savings	Solar-assisted systems reduce electricity-based cooling demand.	Significant peak-load reduction possible during summer months.	TES sizing and hybridization influence total energy savings.
Performance Stability	Real-time control reduces COP fluctuations.	Humidity and variable irradiance challenge system stability.	AI-driven prediction and adaptive system tuning improve resilience.

### 5.2 Simulation-Based Performance Evaluation (TRNSYS, EnergyPlus)

Simulation plays a foundational role in evaluating the dynamic performance of solar-assisted absorption cooling systems, particularly in climates with variable solar resources such as the Northeastern United States. TRNSYS enables hour-by-hour thermal-system simulation, capturing transient behaviors, collector performance, absorption cycle thermodynamics, and TES charging dynamics (Mehmood et al., 2023). EnergyPlus complements this by providing detailed modeling of building loads, envelope heat transfer, and HVAC system integration, thereby supporting holistic campus-scale performance evaluations (Huang and Hu, 2022).

Distributed storage modeling research shows that TES behavior significantly influences system stability under fluctuating weather conditions, enabling simulations to capture rapid irradiance transitions and load-matching constraints (Onuorah et al., 2019). Climate-system interaction modeling reinforces the importance of incorporating humidity,

diffuse radiation, and cloud-cover variability into simulation environments to accurately reflect Northeastern climatic behavior (Agaba et al., 2024). Numerical modeling under fluctuating thermal loads provides insights into generator temperature control, crystallization risk, and absorber saturation limits (Huang and Hu, 2022). Digital-twin simulation frameworks further improve predictive accuracy by integrating real-time sensor data with simulation models, enabling dynamic calibration and enhanced forecasting of performance degradation, thermal losses, and solar fraction variability (Enyejo et al., 2024). Simulation-based evaluation thus enables detailed assessment of COP variation, collector field efficiency, TES sizing requirements, and hybridization strategies, yielding system designs optimized for both performance and resilience.

### 5.3 Empirical Case Studies from the Northeastern U.S. and Similar Climates

Empirical case studies from the Northeastern United States provide critical insights into the operational viability of solar-assisted absorption cooling systems in humid, variable-irradiance environments. Field investigations in mid-latitude climates demonstrate that system performance is strongly influenced by cloud-cover variability, diffuse radiation dominance, and high latent cooling loads (Yoon et al., 2021) as shown in figure 4. Empirical validation studies further show that LiBr-water absorption chillers operate efficiently when generator temperatures remain stable despite fluctuating solar input, highlighting the importance of TES and auxiliary-heat integration (Aliane et al., 2016). Structural and energy-constraint assessments in Northeastern institutions underscore the impact of older building stock, limited roof load capacity, and constrained collector placement on achievable solar fraction (Ocharo et al., 2023). Campus-specific climate-response studies reveal that dense campus building geometries, shading from adjacent structures, and variable occupancy patterns introduce additional complexities that influence system stability and output.

Adaptation strategies used in humid climates such as enhanced dehumidification, high-efficiency absorber coatings, and predictive generator-temperature control have proven effective in overcoming performance degradation associated with high moisture levels (Bashiru et al., 2024). Environmental parameter modeling highlights the need for sensors capturing microclimatic variations, enabling better calibration of control systems and improving COP performance (Ayoola et al., 2024). These empirical findings confirm that solar-assisted absorption cooling can operate effectively in the Northeast when supported by optimized collector fields, TES integration, and adaptive hybridization strategies.

The second branch, *Campus Infrastructure Case Insights*, highlights how institutional building diversity ranging from laboratories with 24/7 loads to intermittent-use classrooms and the constraints of aging rooftop structures, limited mechanical room space, and complex district cooling networks affect system integration feasibility. The third branch, *Cross-Regional Comparisons*, contrasts Northeastern case results with climates such as mid-latitude coastal zones, humid continental regions, and arid or high-altitude areas, showing how differences in solar irradiance stability, humidity loads, and seasonal solar swings shape collector efficiency, solar fraction, and absorption-cycle stability. Collectively, the diagram demonstrates that successful deployment of solar-assisted absorption cooling systems in the Northeast depends on a synergy between climatic adaptability, infrastructure readiness, and lessons learned from analogous climate environments.

### 5.4 Environmental and Lifecycle Impact Assessment

Environmental assessment of solar-assisted absorption cooling systems shows substantial ecological advantages relative to conventional vapor-compression systems, primarily through reductions in electricity consumption and elimination of high-GWP refrigerants. Lifecycle studies indicate that solar-thermal cooling systems reduce greenhouse-gas emissions across their operational lifespan by 35–60%, depending on collector manufacturing impacts and auxiliary-energy use (Mahmud et al., 2018). Eco-efficiency analyses further show that LiBr-water systems outperform ammonia-water cycles in institutional settings due to lower embodied energy and reduced corrosion-control requirements (Shao and Wang, 2021).

Thermomechanical lifecycle models reveal that long-term system degradation such as absorber corrosion, collector stagnation, or TES insulation decay must be incorporated into predictive assessment frameworks to avoid underestimating environmental burdens (Enyejo et al., 2024). Sustainability evaluation studies emphasize that solar-thermal systems yield the greatest environmental benefits when integrated into decarbonization-oriented campus energy strategies. Predictive environmental modeling enables precise quantification of impacts arising from variable solar resource profiles, fuel-mix changes, and auxiliary-heat demand (Shao and Wang, 2021).

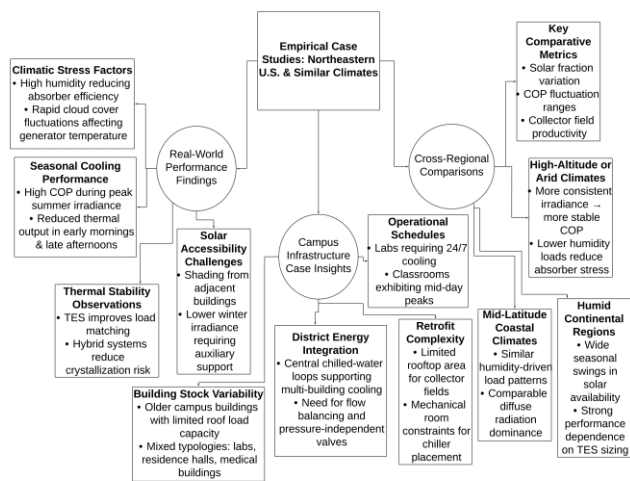
Lifecycle costing research shows that maintenance frequency, collector field replacement cycles, and auxiliary-heater fuel trends play significant roles in determining long-term ecological performance (Ojuolape et al., 2025). In the Northeastern U.S., where solar availability fluctuates seasonally, hybridization strategies and high-efficiency TES systems are essential to maximizing environmental benefits. Overall, lifecycle assessment confirms that solar-assisted absorption cooling offers a low-carbon, environmentally resilient alternative for institutional campuses.

### 5.5 Cost-Benefit and Payback Period Analysis

Cost-benefit analysis of solar-assisted absorption cooling systems shows that although initial capital investment is higher than conventional cooling, lifecycle benefits justify deployment, particularly in institutional campuses with large, continuous cooling loads. Economic viability analyses show that collector field cost, absorption chiller capacity, and TES integration dominate capital expenditure, while reductions in electricity consumption drive long-term savings (Abed et al., 2022). Payback periods typically range from 7–15 years depending on solar fraction, financing incentives, and auxiliary-energy prices (Ferreira et al., 2020).

Economic optimization studies highlight the need for integrated financial modeling that considers not only equipment cost but also avoided peak-demand charges and resilience benefits associated with reduced grid dependency (Enyejo et al., 2024). Distributed energy-system cost modeling further demonstrates that hybrid configurations combining solar thermal, TES, and auxiliary heating achieve superior economic performance by reducing operational volatility (Ocharo and Omachi, 2022). Institutional economic analyses emphasize that Northeastern campuses must account for structural retrofits, roof-load reinforcements, and control-system upgrades, which can increase capital cost but significantly improve system reliability and long-term return on investment.

Techno-financial modeling for hybrid systems also underscores the value of optimizing collector orientation, TES capacity, and generator-temperature settings to minimize lifecycle cost (Oloko et al., 2025). In summary, when appropriately engineered and optimized, solar-assisted absorption cooling systems deliver strong financial performance, substantial operational savings, and favorable payback periods especially for institutions with sustainability mandates.



**Figure 4 :** Empirical case study diagram showing climate impacts, infrastructure constraints, and performance patterns for solar-assisted cooling systems.

Figure 4 provides a structured synthesis of empirical case studies conducted in the Northeastern United States and comparable climate regions, illustrating how real-world operational patterns, campus infrastructure conditions, and cross-regional climate characteristics collectively influence the performance of solar-assisted absorption cooling systems. At the center is the main node, representing empirical findings, which branches into three critical domains. The first branch, *Real-World Performance Findings*, captures field-measured technical behaviors such as seasonal COP variability, humidity-induced absorber inefficiency, rapid cloud-driven thermal instability, and the key stabilizing role of thermal energy storage and hybrid auxiliary heating.

## 6. CHALLENGES, OPPORTUNITIES, FUTURE DIRECTIONS AND CONCLUSION

### 6.1 Technical and Operational Challenges

Solar-assisted absorption cooling systems face numerous technical and operational challenges, particularly in regions such as the Northeastern United States where climatic variability affects thermal stability. One of the primary constraints is maintaining consistent generator temperatures despite fluctuating solar irradiance, which can lead to reduced COP performance and risk of crystallization in LiBr–water systems (Li and Xu, 2020). Operational stability is further compromised by high humidity levels characteristic of the Northeast, increasing absorber load and reducing mass-transfer efficiency. Rapid irradiance changes caused by cloud movement introduce additional instability, requiring advanced control algorithms to balance solar input with auxiliary heating. Maintenance complexity also presents challenges, as absorption chillers demand precise monitoring of solution concentration, vacuum integrity, and heat-exchanger fouling. Seasonal challenges particularly during winter months limit collector effectiveness, requiring hybridization strategies that increase operational costs. Integration with existing district cooling systems introduces hydraulic balancing issues, especially when legacy infrastructure has insufficient sensorization or outdated flow-control mechanisms. Additionally, thermal energy storage systems must be carefully sized to mitigate transient instability and ensure adequate capacity for late-afternoon cooling peaks. Collectively, these technical burdens necessitate robust system design, continuous monitoring, and adaptive control strategies to achieve reliable performance within Northeastern climatic constraints.

### 6.2 Cost, Market Barriers, and Institutional Procurement Limitations

Despite strong environmental benefits, solar-assisted absorption cooling systems encounter substantial economic and market-related barriers that hinder widespread institutional adoption. High upfront capital costs associated with solar collector fields, thermal storage units, and absorption chillers remain the most significant limitations, particularly for universities and research campuses with constrained budgets (Obuseh et al., 2025). Market fragmentation in solar-thermal technologies leads to limited vendor competition and fewer standardized procurement pathways, increasing acquisition risk for institutional planners. Additionally, long payback periods often exceeding conventional funding cycles conflict with institutional requirements for rapid return on investment, thereby discouraging deployment. Procurement processes within large universities frequently involve multi-stage approval cycles, strict financial oversight, and extensive compliance documentation, slowing project advancement. Uncertainty in state-level incentives, coupled with fluctuating energy prices, further complicates long-term economic forecasting needed for procurement justification. Many campuses also lack internal technical expertise for evaluating solar-thermal proposals, requiring external consulting services that increase soft costs. Furthermore, institutions often prioritize investments in visible renewable projects, such as rooftop photovoltaics, over behind-the-meter thermal systems that provide less public visibility despite stronger energy-saving potential. These combined economic and procurement limitations underscore the importance of targeted incentive mechanisms and improved risk-sharing frameworks to support broader adoption.

### 6.3 Technological Advances: High-Efficiency Collectors and Smart Controls

Recent technological advances have significantly enhanced the performance capabilities of solar-assisted absorption cooling systems through improved solar collectors and intelligent control architectures. High-efficiency evacuated-tube and concentrating collectors now achieve substantially higher thermal outputs under diffuse radiation, a critical improvement for Northeastern climates with frequent overcast conditions (Elkelawy et al., 2024). Enhanced absorber coatings and selective surfaces increase optical efficiency while reducing thermal losses, enabling collector fields to maintain generator temperatures required for stable absorption-chiller operation even during suboptimal weather. Parallel advancements in thermal energy storage such as phase-change materials with tailored melting points allow for smoother load shifting and improved late-afternoon cooling availability. Smart control platforms leveraging IoT sensors, machine learning, and digital twins now facilitate real-time optimization of flow rates, solution concentrations, and generator temperatures. These systems can dynamically adjust to cloud transients, occupancy fluctuations, and district cooling demands, greatly improving COP stability. Predictive algorithms also enhance fault detection, enabling proactive maintenance and minimizing downtime. Together, these technological innovations substantially reduce

operational risk, increase energy savings, and expand the feasible deployment range of absorption cooling systems in institutional settings.

### 6.4 Policy Implications and Incentive Frameworks

Effective policy frameworks are essential for increasing the adoption of solar-assisted absorption cooling systems within institutional campuses. Renewable thermal technologies often receive less policy support than electricity-generating systems, resulting in inadequate incentives and slower market development (McMillan et al., 2023). Expanding state-level incentive programs such as renewable thermal credits, performance-based rebates, and low-interest financing can significantly improve economic feasibility for universities and research institutions. Policies that incorporate lifecycle carbon accounting into institutional procurement requirements further strengthen the justification for transitioning to solar-assisted cooling (Agbaje and Idachaba, 2018). Additionally, building-energy codes could integrate provisions encouraging thermal renewable adoption, such as mandatory feasibility assessments for large new constructions or major retrofits. At the federal level, aligning thermal renewable incentives with decarbonization targets would create long-term market confidence. Universities operating under public governance often face administrative and legal constraints that slow adoption; thus, policy frameworks that simplify procurement pathways and support public–private partnerships can accelerate project deployment. Clearer guidance on integrating solar-thermal systems with existing district energy networks would also mitigate technical uncertainty. Overall, a strong combination of financial incentives, regulatory support, and institutional policy alignment is necessary to unlock the full potential of solar-driven absorption cooling systems across Northeastern campuses.

### 6.5 Conclusion and Recommendations for Future Research

Solar-assisted absorption cooling systems present a technically viable and environmentally advantageous pathway for reducing institutional energy demand, enhancing operational resilience, and supporting long-term decarbonization goals in the Northeastern United States. The findings of this review demonstrate that meaningful performance improvements depend on effective integration of high-efficiency solar collectors, robust thermal energy storage, and advanced control strategies capable of managing fluctuating irradiation patterns and humidity-driven load variations. Empirical and simulation-based analyses consistently indicate that system stability hinges on aligning collector field output with generator temperature requirements while mitigating transient disruptions caused by rapid cloud movements and seasonal irradiance shifts. Building typology, structural constraints, and district-energy compatibility further influence deployment feasibility, underscoring the need for campus-specific engineering assessments.

Future research should prioritize the development of adaptive, AI-driven control architectures capable of predicting cooling loads, optimizing auxiliary heating schedules, and dynamically regulating solution concentrations to prevent crystallization and enhance COP stability. Innovations in phase-change thermal storage materials and modular concentrating collectors also represent promising avenues for improving energy density and reducing spatial requirements in space-constrained campuses. Longitudinal field studies across diverse institutional settings would help establish standardized performance benchmarks and refine lifecycle assessment methodologies. Additionally, techno-economic modeling should evolve to incorporate uncertainty quantification, policy sensitivity analysis, and resilience-based valuation metrics that capture the full operational and societal benefits of solar-assisted absorption cooling.

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