A Comparative Review and Novel Design Possibilities on Solar-Driven Absorption LiBr-H_2O Refrigeration System

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Abstract. Solar energy emerges as a promising renewable resource to mitigate reliance on non-renewable energy sources, especially in addressing the escalating demand for cooling. LiBr-H_2O absorption chillers, preferred over NH_3-H_2O systems, are widely employed in solar cooling technologies, driven by flat-plate, evacuated tubular, or parabolic solar collectors. This paper presents a Theoretical Principles-Based Analysis and Simulations of solar LiBr-H_2O absorption cooling systems, conducting a comprehensive performance comparison, and introducing innovative design options for auxiliary energy systems and cooling mode cycles. Furthermore, it delves into various solar absorption cooling systems, including double-effect, half-effect, and triple effect, providing updates on hybrid effect technology. The choice between water-cooled and air-cooled absorption refrigeration hinges on local climate and water availability. Recent advancements have positioned air-cooled absorption refrigeration as a viable alternative, demonstrating comparable Coefficient of Performance (COP) to water-cooled systems with reduced maintenance requirements. Incorporating geothermal heat rejection with low pressure drops further augments energy efficiency. Recommendations advocate solar-powered double-effect absorption cooling systems for structures with high cooling loads and half-effect systems for air-cooled applications in arid regions. The paper underscores the imperative of standardized design guidelines tailored to specific regional and climatic considerations, facilitating the widespread integration of solar cooling systems.

Keywords: *solar absorption refrigeration; performance comparison.*

1 Introduction

Global electricity demand is increasing in every sector [1], and renewable energy such as solar energy is rapidly growing to meet this demand as coal usage decreases [2–4]. Utility-scale solar PV is the least costly option for new electricity generation in a significant majority of countries worldwide, despite current higher investment costs due to elevated commodity prices. The International Energy Agency (IEA) predicts that cumulative solar PV capacity will nearly triple, surpassing natural gas by 2026 and coal by 2027, with annual capacity additions projected to increase for the next five years [5].

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Refrigeration systems contributed for nearly 20% of the total electricity used in buildings around the world today [6]. Energy consumption for space cooling has more than tripled since 1990, with significant implications for electricity grids. 2021 was one of the seven warmest years on record. In addition, the past seven years have been the hottest ever recorded. Space cooling demand experienced the highest annual growth among all buildings end uses in 2021 and accounted for nearly 16% of buildings sector final electricity consumption (about 2000 TWh) [7]. Rising demand for space cooling is also putting enormous strain on electricity systems in many countries, as well as driving up emissions [8]. Solar-driven refrigeration system was considered viable and promising system due to its driven by clean and renewable energy source which is solar radiation [9, 10].

Compression chillers operate by using electrical energy to compress a refrigerant, while absorption chillers use thermal energy as an alternative energy source to generate cooling [11]. Compared to compression chillers, absorption chillers offer two primary advantages: the ability to utilize renewable energy sources such as solar energy, geothermal energy, and waste heat from industrial processes as their primary input, and their compatibility with the environment [12, 13]. LiBr-H_2O is a type of absorption refrigeration system that able to utilizes solar energy as a heat source to drive the refrigeration cycle. LiBr-H_2O absorption chillers are preferred over NH_3-H_2O absorption chillers due to their higher COP and does not having toxicity issues [14]. The system consists of several components, including the absorber, generator, condenser, and evaporator. LiBr-H_2O refrigeration systems can be classified into three categories based on their performance and configuration: single-effect, double-effect, and other main types such as triple-effect, half-effect and resorption). Each category has its own unique features, advantages, and limitations, making it suitable for different applications.

The aim of this paper is to provide a review and technology updates of the solar-driven LiBr-H_2O refrigeration system and its various categories, with a focus on their performance, efficiency, and potential for reducing the environmental impact of refrigeration systems and their compatibility with solar energy. In addition, This paper will also present the development of new design of hybrid effect.

2 Absorption Chiller System Description

2.1 Single-Effect Libr-H_2O Absorption Chiller

The utilization of water/lithium bromide as the working fluid in a single-effect absorption cycle is considered to be a fundamental application of absorption heat pump technology. The hardware configuration of the single-effect absorption cycle consists of two cylindrical shells, with each shell containing two components that operate at similar pressures. For instance, the evaporator and absorber are located in the same shell. Although a pressure difference is required for the flow from the evaporator to the absorber, the open geometry of the system minimizes this difference.

A cycle schematic, depicted in Figure 1, illustrates the external energy transfers in the cycle through arrows, with variable names representing the four heat transfer rates where heat source of $\dot{Q}g$ supplied by hot water or steam, the heat absorption $\dot{Q}e$ is from chilled water, both $\dot{Q}a$ and $\dot{Q}c$ are heat that released to cooling media such as cooling water (water-cooled) or ambient air (air-cooled). The cycle schematic is drawn as if it were superimposed on a Dühring chart shown in Figure 2, which indicates the coordinates of the working fluid properties in the lower left-hand corner.

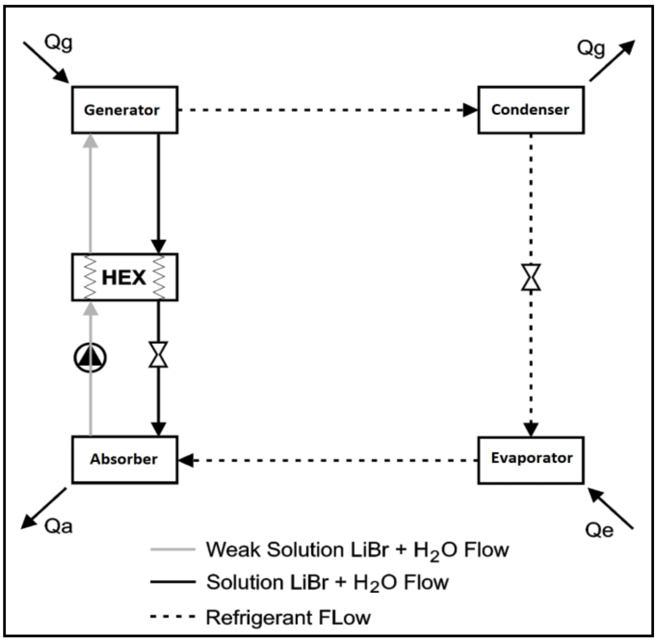

Figure 1 Single-effect LiBr-H_2O Cycle

The Dühring plot shown in Figure 2, is used to visualize and analyze the thermodynamic properties of a liquid-vapor system. It plots the concentration of one component in the liquid phase versus the concentration of the same component in the vapor phase, at a given temperature and pressure. By analyzing the slope and intercept of the plot, the vapor-liquid equilibrium properties can be determined such as the activity coefficients and the partial vapor pressures, of the system. This information is important for designing and optimizing absorption chillers, as it helps to understand the behavior of the working fluid at different operating conditions.

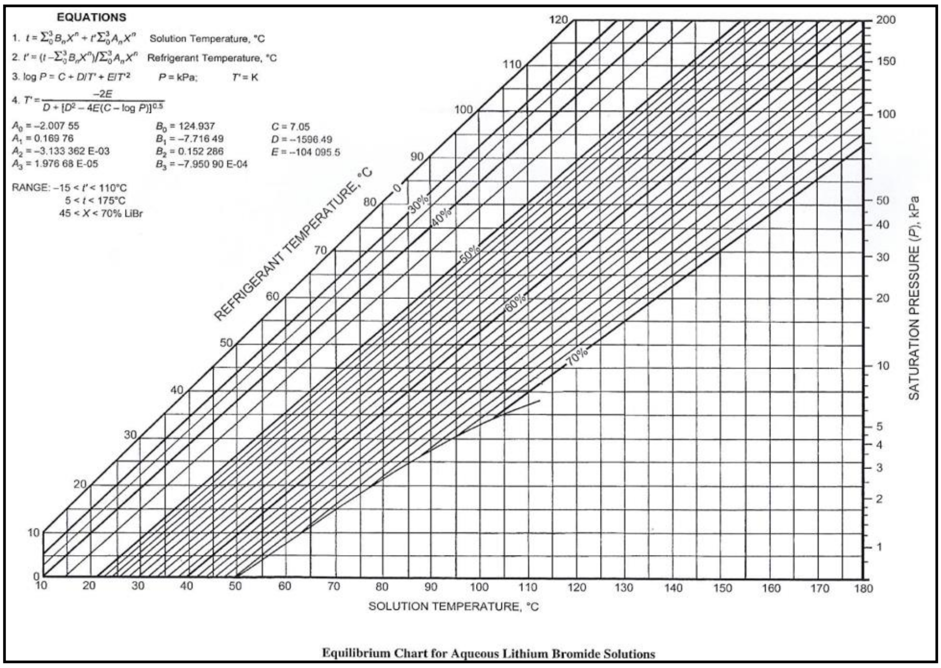

Figure 2 Dühring plot for the LiBr-H_2O solution [15]

2.2 Double-Effect Libr-H_2O Absorption Chiller

Single-effect technology is 8challenged by its relatively low COP, making it difficult to compete economically with conventional vapor compression systems. However, in low-temperature waste heat applications where the input energy is free, single-effect machines can be more viable. Kurosawa and Yoshikawa [16] and Wilkinson [17] found that double-effect technology, which has a COP in the range of 1.0-1.4, is much more competitive than single-effect machines. The high end of the COP range represents the cycle COP, which could potentially be achieved by firing the machine with waste heat.

Double-effect absorption has two generators: HPG as the main generator and LPG as the secondary generator. HPG receives heat from the source (Qg) to generate refrigerant. LPG is a heat exchanger that has a dual function as a generator and condenser. The refrigerant (output from HPG) releases heat into the strong solution (output of the generator). The purpose of LPG is to generate more refrigerant from the strong solution, resulting in a higher amount of refrigerant produced and an increased COP.

Double-effect absorption has two types: double-effect series and double-effect parallel flow. The difference is in the input circuit for LPG. In series flow, the strong solution flows in series from HEXH to HEXL. Meanwhile, in parallel flow, the weak solution (which comes from HEXL) flows to two components: HEXH and LPG. Double-effect series and parallel flow are shown in Figure 3 and Figure 4.

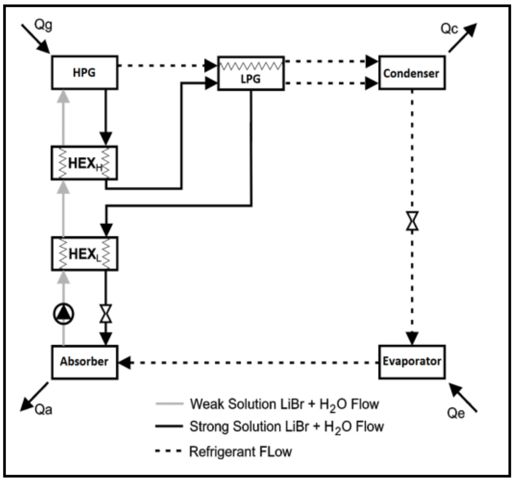

Figure 3 Double-effect series LiBr-H_2O cycle

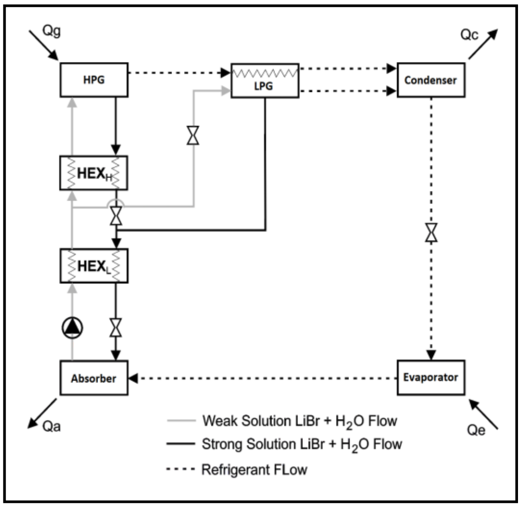

Figure 4 Double-effect parallel LiBr-H_2O cycle

2.3 Half-effect LiBr-H_2O Absorption Chiller

In cases where the temperature of the available heat source is below the required threshold for triggering a single-effect cycle, the half-effect cycle presents itself as a potential solution. The determination of the minimum temperature needed for a single-effect cycle is a complex process, as it is dependent on the chilled water temperature and the heat rejection temperature. However, when the heat source temperature is too low, the properties of the working fluid limit the options for utilizing the low-temperature heat source. Therefore, the half-effect cycle emerges as a practical alternative in such instances.

Half-effect machine is a three-pressure-level machine that incorporates an intermediate-pressure level in addition to the high- and low-pressure levels, which function similarly to those found in single-effect systems. This unique feature allows the low generator to release refrigerant vapor to the high absorber, while the high solution circuit transports the refrigerant to the high generator for a second boiling process before it passes through the condenser, evaporator, and low absorber as per standard procedure.

The half-effect machine has a unique characteristic in that the required heat input temperature is lower than that of a single-effect machine with the same chilled water and heat rejection temperatures. However, this benefit comes at a thermodynamic penalty, as the cycle must be triggered at a lower temperature. Consequently, the cooling COP of a half-effect machine is typically about half that of a single-effect machine. For instance, a water/lithium bromide half-effect machine is estimated to have a COP of approximately 0.4 [18]. The half-effect cycle is a three-pressure-level system that requires a lower heat input temperature than the single-effect cycle. Compared to the double-effect cycle, the half-effect cycle has a lower COP, and two units of heat are required for one unit of refrigerant. The cycle is suitable for scenarios with low-temperature waste heat where the heat input temperature is too low for the single-effect cycle to operate. The half-effect cycle, with its intermediate-pressure level, can efficiently receive heat at lower temperature than single-effect cycle. Notably, both cycles provide refrigeration at the same temperature. A cycle schematic, depicted in Figure 5.

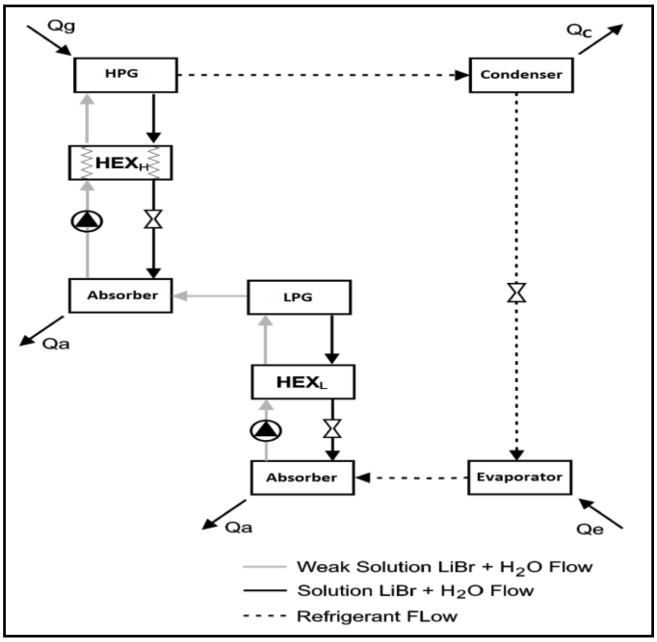

Figure 5 Half-effect LiBr-H_2O cycle

2.4 Triple-Effect LiBr-H_2O Absorption Chiller

From 1996 to 2005, major absorption equipment manufacturers experienced a significant development phase of the Triple-Effect technology, as reported by Kujak and Schultz [19], Yabase et al. [20], and Yabase and Makita [21]. The main advantage of the Triple-Effect cycle is that it can increase the COP to the range of 1.4–1.6 with only a modest increase in first cost. However, the main challenges associated with this concept, and with Triple-Effect concepts in general, are corrosion and materials. Due to the higher temperatures involved, traditional materials of construction can experience significant increases in corrosion rates. Thus, most Triple-Effect concepts focus on solving the high-temperature corrosion challenge, as reported by Jiangzhou and Wang [22].

Compared to a double-effect absorption chiller, a triple-effect chiller has a higher capacity because it generates more vapor per unit of heat input, providing more refrigeration capacity to the evaporator. Assuming a burner efficiency of 90%, the cooling COP for a triple-effect configuration is 1.48, which represents the upper limit of practical performance potential. However, practical design trade-offs may result in reductions in that value. The percentage improvement in cooling COP obtained in going from double to triple-effect is less than that obtained in going from single to double-effect, as per the superposition principles of Alefeld and Radermacher [23]. A double-effect machine should achieve a COP of 1.24, while a triple-effect machine should achieve 1.61. In practice, double-effect machines are often built with design compromises that result in a COP of 1.0. Similarly, if triple-effect machines are built with similar compromises, a realistic performance projection for gas-fired triple effect is a cooling COP of 1.3. Therefore, the actual cooling COP for triple-effect is expected to be in the range between 1.3 and 1.48 [18]. A Triple-effect schematic, depicted in Figure 6.

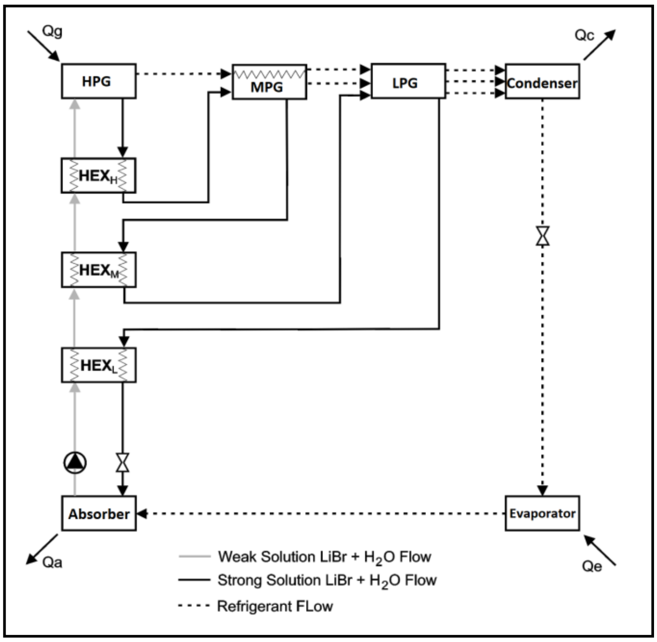

Figure 6 Triple-effect LiBr-H_2O cycle

3 Solar-Powered Single-Effect LiBr-H_2O Absorption Chiller

The performance analysis of a single effect solar-driven lithium bromide/water absorption cooling system will be conducted through a combination of experimental investigations and theoretical simulations. The experimental investigation will involve a comprehensive analysis of the system's energy performance, providing accurate results and real-world data. Conversely, the theoretical analysis and simulations will utilize theoretical principles to study the system's behavior under various conditions. While experimental investigations are valuable, they can be costly and time-consuming. In contrast, simulations offer a cost-effective and efficient approach to predict the system's performance and optimize its operation, making them a favorable option considering development costs.

3.1 Experimental Investigations

Gao et al. [24] carried out an experiment on a solar-driven absorption refrigeration integrated with single and double stage thermal storage. The aim of the project was to provide a feasible option for large-scale utilization and prolongation of solar energy, as well as provide stationary heating output during winter. Both long-term heat storage and short-term heat/cold storage were tested and evaluated for the double-stage and single-stage working modes. In the charging process, hot water at 75-85°C was used as a heat source to simulate solar energy from a non-concentrated collector, resulting in a heating output/cooling output at 50/11°C in the discharging process. The study achieved an energy storage density of 103 kWh/m^3 for heating output with a temperature lift of 30-46°C, which was 2.51 times higher than that of the single-stage system.

Chen et al. [25] conducted experimental for a novel 5kW air-cooled single-effect LiBr-H_2O absorption chiller suitable for residential solar refrigeration applications. The chiller incorporates an adiabatic flash evaporator and absorber to minimize the risk of crystallization and facilitate miniaturization. The elimination of the chilled water circulation pump and heat transfer pipes in the evaporator through adiabatic flash process improves the COP, cooling capacity, and reduces material costs and electricity consumption. The chiller was tested under different operating conditions, and experiments revealed that an evaporation temperature of 8.6°C can be achieved. With a raised evaporation temperature at 14.5°C, the chiller was able to control indoor air temperature to 26.6°C when the ambient temperature was 35°C. The cooling capacity and COP under low and high ambient temperature are 5.3 kW/0.72 and 4.6 kW/0.65, respectively. The thermal COP ranged from 0.76 to 0.64 when the hot water temperature was raised from 80°C to 90°C. During the 9-hour outdoor experiment, the average thermal COP was 0.65, and the average cooling capacity was 5 kW.

Chen et al. [26] conducted an experiment of Solar air-cooled single-effect LiBr-H_2O absorption chillers to mitigate the risk of crystallization under ambient conditions. This study developed and tested an air-cooled single effect absorption chiller with a cooling capacity of 6 kW under various steady-state conditions, which proved to be successful without crystallization risk. The performance of a solar air conditioning system using the proposed chiller was also investigated for residential cooling application. Results indicate that the studied absorption chiller can meet around 65% of the building's total cooling load with an average COPth of about 0.61. Furthermore, the solar air conditioning system can convert 28% of the titled solar radiation into cooling capacity.

Ha Q and Vakiloroaya V [27] conducted a study on a solar-powered, 6 kW hot-water single-effect absorption chiller air conditioning system that aims to address critical issues of electricity consumption and greenhouse gas emissions. The system, which is fully powered by solar radiation and does not require water storage or auxiliary heat exchanger. The influence of various temperatures on the system's performance, including chilled water, cooling tower water, and solar collector hot water temperatures have been investigated. The experimental results demonstrate the technical feasibility of the proposed system in meeting air-conditioning demands while reducing electricity consumption and greenhouse gas emissions. Moreover, it was found that the hot water temperature leaving the solar collector has a significant influence on the chiller performance since increasing the hot water temperature can increase the chiller cooling capacity.

Beausoleil-Morrison et al [28] carried out an experiment on a lithium bromide-water absorption chiller under controlled operating conditions to assess the potential of small-scale solar air conditioning systems. A quasi-steady-state model for building performance simulations was developed, with cooling capacity ranging from 6.9 kW to 40.5 kW and thermal COP from 0.56 to 0.83. Heat transfer rates for the generator and evaporator were found to be linear functions of generator inlet temperature, absorber/condenser inlet temperature, and water flow rate to the generator. The calibrated model was validated using a separate experiment.

Li et al [29] investigated the performance of 23 kW single-effect LiBr-H_2O absorption cooling system powered by solar energy. Power supply was powered by 56 m2 parabolic trough collector. The study revealed that the chiller's refrigeration coefficient reached maximum of 0.6. While the daily solar heat fraction ranged from 0.33 to 0.41 on clear days, and the cooling COP varied from 0.11 to 0.27.

Experimental studies absorption cooling process have been conducted by several researchers for both resigodential and public buildings. The COP of experimental studies were ranging from 0.43-0.83. The experiments were summarized and presented in Table 1.

Table 1 Single Effect Experimental

References	COP
Gao et al [24]	0.43
Chen et al [25]	0.64- 0.76
Chen et al [26]	0.61
Beausoleil-Morrison et al [28]	0.56 - 0.83
Li et al [29]	0.11 - 0.27

3.2 Theoretical Principles-Based Analysis and Simulations

Marashli et al [30] presented a project that aimed to evaluate the possibility of utilizing a solar-powered LiBr-H_2O absorption refrigeration system in Jordan. The MATLAB/Simulink environment was utilized to develop a model of the system based on the maximum wet-bulb temperature (25°C) for the area, which was acquired from the Jordan Meteorological Department. The most influential factor on the COP value was found to be the generator temperature, which increased the COP by 27.4% when it was raised from 95°C to 105°C. The optimal refrigeration system that met the 120 kW cooling capacity requirement without experiencing crystallization utilized a solar collector area of 243.3 m^2 and achieved its highest performance when the generator, absorber, condenser, and evaporator temperatures were maintained at 105°C, 30°C, 50°C, and 5°C, respectively. Under these conditions, the system achieved a COP of 0.745, an effectiveness of 0.8, and received a solar radiation value of 1033 W/m^2.

Sharifi et al [31] presented a project that aimed to advance the performance of a single-effect lithium bromide/water absorption refrigeration system by optimizing the generator and evaporator temperatures as variables to maximize exergetic and energetic efficiencies at different operational conditions using a multi-objective-multi-variable genetic algorithm. Following the simulation of the cycle, the optimization was performed using GMDH, which was repeated for various operational conditions to generate a database for the COP, exergetic efficiency, and generator and evaporator temperatures. The results then coupled to the solar collector developed by Bellos et al. [32]. By decreasing the mean temperature of the generator by approximately 6.2°C and increasing the mean temperature of the evaporator by 1.6°C, a significant improvement in the energetic efficiency (3.6%) and a slight improvement in the exergetic efficiency (0.6%) were achieved. The optimized system's higher performance resulted in significant cost savings of $187 per square meter of solar collector and a decrease in carbon dioxide emissions of about 33.5 kg per square meter of solar collector.

Hu et al [33] reported a comprehensive approach to improving the utilization of solar energy using a spectral-splitting hybrid PV thermal system integrated with a LiBr-H_2O absorption refrigeration system. The model was developed using mathematical modelling and was subsequently optimized to enhance the surplus heat utilization and boost the overall efficiency of the system. The results showed a significant improvement in the overall energy efficiency, which reached 59.26%, a 25.56% increase compared to the non-optimized parameters. The overall exergy efficiency was found to be 37.51%, with the highest exergy destruction occurring in the solar cell, resulting in a total of 73.98% exergy loss.

Basu D and Ganguly [34] A proposed conceptual design for a potato cold storage system and performance evaluation over a year. The system regulates the microclimate inside the storage facility through a water-lithium bromide absorption system and utilizes solar thermal and PV energy sources. The integrated system's energy and exergy performance are analyzed to determine the necessary number of thermal collectors and PV modules based on Kolkata weather. The proposed system produces a net energy surplus of approximately 36 MWh per year, after satisfying the in-house requirements. Furthermore, the system having payback periods of less than four years.

Liu et al. [35] studied the use of a solar-powered absorption chiller for residential cooling and found that the instability and intermittency of solar energy hinder its effectiveness. To mitigate this, an integrated absorption heat storage and absorption refrigeration process using a dynamic numerical model solved by nonlinear programming and second-order iterative numerical integration has been investigated. Results showed that the proposed system increased total refrigerating capacity and average performance coefficient by 4.44% and 3.5%, respectively, compared to the reference system. The total cold storage capacity of the integrated system was also found to reach 6890.4 MJ/day, which extends the cooling time to approximately 14 hours.

Camara S and Sulin A [36] performed a study aimed to develop a mathematical model for a DASC that could be used for both daytime solar heating and nocturnal radiative cooling with a 17.6kW single-effect absorption chiller LiBr-H_2O. The performance of the DASC was analyzed throughout the day, and an optimization study was conducted on the SEAC's operating parameters under the Bamako weather conditions. The solar collector had a thermal efficiency of 0.734 and a heat loss of 4.51 W/(m2K) during the day, and it produced an average net radiative cooling power of 58.74 W/m2 at night with zero reduced temperature.The absorption chiller LiBr-H_2O achieved a COP of 0.87, and the overall system had a performance of 0.64.

Based on the Theoretical principles-based analysis and simulations, The solar-driven single-effect absorption chillers have the potential to provide a feasible option for large-scale utilization. These systems have been shown to be effective in providing stationary heating output during winter and meeting cooling demand for residential applications. The studies also show that there are a variety of design options available for single-effect absorption chillers, including air-cooled and water-cooled designs, as well as different types of thermal storage.

4 Solar-Powered Double-Effect LiBr-H_2O Absorption Chiller

Double-effect cycles were preferably studied for larger residential or public buildings due to their potential for achieving a higher COP and ability to handle greater cooling demands than single-effect cycles. The experimental investigation, although more costly, is worthwhile in cases of higher cooling demands. Theoretical principles-based analysis and simulations offer a wide range of design options for the double-effect cycle.

4.1 Experimental Investigations

Li et al. [37] investigated a solar air-cooled double-effect LiBr-H_2O absorption refrigeration system that operates without a cooling tower and independent of water, making it an attractive option for commercial and residential buildings. The study focused on the system's performance with respect to the collector temperature in a subtropical city, using an array with an aperture area of 27 m2, a tilt angle of 20 degrees towards the south, an evaporator temperature of 5°C, and a cooling capacity of 20 kW. A parametric model was developed based on meteorological data collected over a year and summarized as a monthly typical day. The study found that the optimal range of the collector's inlet temperature is between 110-130 °C to enhance performance and reduce the risk of crystallization. The COP of the year was ranging from 1.14 to 1.215 and the average solar collector efficiency was 0.437.

Lu Z and Wang R [38] carried out an experiment by comparing the three different solar collectors which integrated with three different options of chiller. The solar collectors can produce hot water ranging from 60-150°C. The study aimed to evaluate the experimental performance and economic feasibility of three small-scale solar refrigeration systems using these different collector-chiller combinations. The results revealed that the solar COP varies among the different systems. For instance, the solar refrigeration system with adsorption chiller and U pipe solar collectors has a solar COP of about 0.15 and can be driven by 55°C hot water. On the other hand, the solar refrigeration system with CPC solar collector and single-effect absorption chiller can achieve a solar COP of 0.24 in sunny weather. The solar refrigeration system with PTC solar collectors has the highest solar COP at about 0.5, and the double-effect LiBr absorption chiller is the most cost-effective option due to its higher solar COP and better overall economy.

Soussi et al [39] conducted an experimental study of an absorption cooling system that used a compound parabolic collector. The solar system was coupled to a 16-kW double-effect lithium bromide absorption chiller. The system achieved a COP range of 0.65–1.29, with a daily maximum solar COP of approximately 35%.

Rossetti et al [40] found COP to be higher than 1 in most operating conditions, while the COP ranged from 0.8 to 1 for 5-10 kW and increased to 1-1.2 for refrigeration power output greater than 10 kW. Hang et al [41] Carried out experimental with the objective to reduce conventional energy consumption and minimize negative environmental impacts by utilizing solar energy is an increasingly promising approach for air conditioning. The solar cooling test facility that uses 54 m2 external compound parabolic concentrator solar collectors to drive a 23 kW double-effect absorption chiller has been built. Energy performance analysis conducted in August 2012 shows that the system can provide sufficient cooling for a test facility between 11 AM and 5 PM on both sunny and cloudy days. The daily average collector efficiency is in the range of 36% to 39%, and the average coefficient of performance (COP) of the LiBr absorption chiller is between 0.91 and 1.02, with an average of 1.0. The daily solar COP is approximately 0.374. From the two solar cooling system configurations, the configuration 2 has better life cycle economic and environmental performance than configuration 1, achieving a lower present worth cost during the entire life span than conventional systems. Both configurations 1 and 2 can reduce the lifetime carbon footprint by 35% to 70%.

The experimental investigation on double-effect cycle has demonstrated that its COP is superior to that of the single-effect cycle. However, it should be noted that the double-effect cycle's COP is constrained by its requirement of a higher heat input temperature compared to the single-effect cycle. The Table 2. summarized these results in terms of COP.

Table 2 Double Effect Experimental

References	COP
Li et al [37]	1.14 - 1.21
Soussi et al [39]	0.65 - 1.29
Rossetti et al [40]	0.80 - 1.20
Hang et al [41]	0.91 - 1.02

4.2 Theoretical Principles-Based Analysis and Simulations

De and Ganguly [42] developed a comparative performance assessment of a single-effect and a double-effect LiBr-H_2O absorption chiller powered through a combination of a grid-interactive solar PV system and parabolic trough collectors. A thermal model and economic model of the system were developed, with the thermal model being built in MATLAB using hourly meteorological data for Kolkata, India as input. The study reveals that double-effect system is estimated to have about 14% lower total thermal exergy loss across the condenser and absorber compared to the single-effect system. Additionally, the maximum COP of the double-effect system is estimated to be 1.32 for a typical day in December. The payback period for the single-effect and double-effect system-based multi-commodity cold storage powered through a solar-thermal-PV system are found to be four years and three years and six months, respectively.

Ibrahim et al. [43] presented a model of an integrated Solar-assisted double effect absorption refrigeration system with absorption energy storage in Dhahran. The Engineering equation solver (EES) was used in this study. The results show that, depending on weather conditions, there is a high risk of solution crystallization during the charging operation when the solution distribution ratio is below 50%, and there is also potential risk when the initial lithium mass fraction is around 55% inside the tank. The optimal operating conditions are achieved with an initial solution mass of 64,000 kg in the storage tank, initial solution LiBr mass fraction of 55%, and a solution distribution ratio of 55%. The highest energy storage density is around 136.8 kWh/m3, with an average cooling effect of 1700 kW, and an overall solar system COP and exergy efficiency of 0.985 and 0.067, respectively. Exergy analysis revealed that the solar collector accounts for approximately 61% of maximum exergy destruction, followed by the high-temperature generator with about 12% contribution.

Ibrahim et al. [44] developed a model of energy storage to extend the cooling period of solar-driven double-effect water-lithium bromide absorption system during unavailability of solar radiation in Dhahran, Saudi Arabia. The absorption energy storage stores the solar heat in the form of chemical energy during the day and discharges later for cooling application. The Engineering equation solver (EES) was used in this study to model the system. The results indicate that the integrated double-effect absorption chiller-storage unit has an average COP of 1.35 and an exergy efficiency of 25%. Moreover, the energy storage density obtained from the integrated double-effect system is found to be 13-54% higher than that of the integrated single-effect configuration.

Ferwati et al. [45] investigated the feasibility of using an ionic liquid-based H_2O mixture, [mmim][DMP] (1,3-dimethylimidazolium dimethylphosphate), as an alternative working fluid to overcome the drawbacks of LiBr-H_2O in double-effect absorption refrigeration systems. The system was modelled and simulated using SCILAB 6.0.2. Compared to the conventional LiBr-H_2O, the proposed H_2O-[mmim][DMP] working fluid achieves a 5.22% and 4.95% improvement in COP and ECOP, respectively. An optimization reveals the highest COP_{max} and $ECOP_{max}$ of 1.81 and 0.69, respectively, for an evaporation temperature of 20°C and a cooling media temperature of 40°C.

Ibrahim et al. [46] performed a parametric study on a solar refrigeration system that includes a parallel-flow double-effect water-lithium bromide absorption chiller and a parabolic trough solar collector. The objective was to size the solar collector field and evaluate the effect of different operating conditions and parameters on system performance. The study was based on a reference double-effect absorption chiller from Broad Company with a nominal cooling capacity of 1163 kW. An optimization process was used to maximize exergy efficiency while considering the risk of solution crystallization, resulting in a solar collector field of 1350 m² (1.16 m²/kW). The results were normalized per unit chiller nominal cooling capacity, facilitating application to different system configurations. Under solar radiation levels of 600-944 W/m², the system achieved cooling effects of 798-1223 kW, with the chiller COP range at 1.29-1.39. The presented procedure can be used for sizing and evaluating similar systems under various climatic conditions with a minimum solar radiation of approximately 500 W/m².

Marcos et al [47] proposed A solar refrigeration system with an optimized air-cooled double-effect water/LiBr absorption machine as a sustainable alternative to meet cooling demands in dry hot climates. In areas where water is limited, this system offers a solution by eliminating the need for cooling towers. The work evaluates the environmental advantages and environmental impacts of this air-cooled system in comparison to a solar water-cooled single effect system. A methodology has been employed to assess the amount of water saved annually based on a case study, which was a hospital situated in the South of Spain's Almería region. The results of the study indicated that the air-cooled system required 35% less energy to meet cooling demands compared to a single-effect solar water-cooled system. Additionally, the proposed system resulted in a total annual carbon dioxide saving of 11,007 tons.

The innovative design options have been created for the double-effect cycle, demonstrating their potential to overcome its limitations. One such limitation is that the cycle requires a higher heat input temperature than single-effect, resulting in a limited COP compared to double-effect compression chiller. However, several new designs have been proven feasible in tackling this challenge. Furthermore, the combination of new working fluids, such as [mmim][DMP], is currently under development and could potentially overcome the limitations of the traditional Lithium bromide-water combination in terms of crystallization.

5 Solar-Powered Based on Other Types Absorption Chiller

Solar-driven absorption chillers are a sustainable and eco-friendly alternative to traditional refrigeration systems that rely on electricity. While single and double-effect absorption chillers are commonly used, there are also other types of absorption chillers that can be used for different applications. These include half-effect, triple-effect, and hybrid cycle absorption chillers. These alternative designs offer different advantages and can be customized to meet specific cooling requirements. In this context, it is important to explore the various types of solar-driven absorption chillers available and their respective benefits to make informed decisions about their use.

5.1 Solar-Powered Half-Effect Absorption Chiller

Volpato et al. [48] investigated the comparison of four main configurations (Single, Half, Double, Resorption) of solar-driven absorption refrigeration systems under the same cooling duty and ambient conditions. The investigation involved modelling approaches for each configuration, with two types solutions tested using the HEATSEP method and EES software. The results provided a clear comparison of the main configurations under the same boundary conditions, with new configurations proposed that showed COP gains higher than 3% in comparison with the best corresponding single-effect system.

Liu et al. [49] developed a new integrated system, comprising a high-temperature proton exchange membrane fuel cell (HT-PEMFC), Kalina cycle, CPV, and a half-effect absorption refrigeration system. Waste heat from HT-PEMFC drives Kalina cycle for increased power output, while lower-grade waste heat from CPV is utilized by the absorption refrigeration cycle for cooling the Kalina cycle's condenser. The result also shown that the half-effect absorption refrigeration system absorbs 123.2kW waste heat from concentrating PV and can provide 50.5kW cooling capacity. The exergy efficiency of PEMFC is increased by 23.99% and the exergy efficiency of CPV is increased by 9.39% compared with the sub-supply system. The COP of half-effect refrigeration system is 0.4104.

Sun et al. [50] developed a novel solution to the challenge of utilizing solar energy for space heating and cooling in China's Northern cities, where the continuous high energy density demand does not match the intermittent energy output of solar energy. They propose a 20,570kW solar-driven low temperature district heating and 5,025 kW refrigeration system based on distributed half-effect absorption heat pumps with lithium bromide. By using thermodynamics and economics, they show that the system can achieve an annual system COP of about 8.52 with 0.39 daily COP for space cooling, an annual system product exergy efficiency of about 36.7%, and cost-effectively heat transmission distance of about 24.5 km.

The half-effect configuration of solar-driven absorption refrigeration systems is a promising alternative to the single-effect system due to its ability to start the thermal cycle with a lower temperature than the single-effect, resulting in improved efficiency. Several studies have explored the potential of the half-effect cycle in different applications. They showed that the system could achieve a high annual system COP and exergy efficiency, with cost-effective heat transmission distances. These studies highlight the potential of the half-effect cycle in improving the efficiency and performance of solar-driven absorption refrigeration systems.

5.2 Solar-Powered Triple-Effect Absorption Chiller

Gogoi T and Hazarika P [51] designed the four novel solar integrated systems which used either a single or two units of a triple effect absorption refrigeration system to produce cooling by utilizing hot water from a solar collector. The power cycles are based on organic Rankine and Kalina cycles. The results show that the integration of the Kalina cycle with the absorption refrigeration system provides better performance in terms of power, efficiency, and irreversibility rate compared to the organic Rankine cycle. At low and high solar radiation intensities, the net power obtained from the Kalina cycle is respectively 7.17% and 7.35% more, while the irreversibility is 16.23% and 16.28% less compared to the organic Rankine cycle. The COP for the absorption refrigeration system was approximately 1.325.

The progress in the last decade regarding the development of triple-effect solar-driven absorption systems has been limited due to their higher temperature requirement to initiate the thermal cycle compared to other cycles. Furthermore, despite their higher input temperature demand, triple-effect cycles have not demonstrated higher COP values than double-effect absorption system.

The temperature requirements for absorption systems vary based on the effect and working pair of H20-LiBr. For half-effect and single-effect absorption systems, have one generator. The generator temperature ranged from 50°C to 70°C for half-effect and 70°C to 95°C for single-effect. In double-effect systems, a high temperature is needed for the generator to operate from 140°C to 170°C. Triple-effect systems have a higher temperature. The high-temperature generator ranges from 190°C to 220°C. These temperature ranges can vary depending on system design, working pair concentrations, and specific requirements. Variation of absorption system effect based on generator temperature is shown in Figure 7.

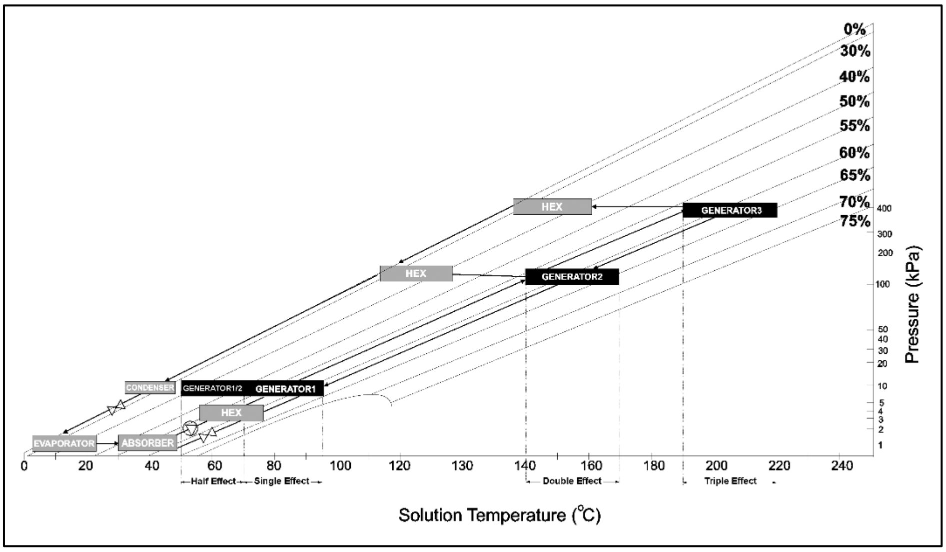

Figure 7 Variation of absorption system effect based on generator temperature

6 New Design Options of Solar-Powered Hybrid-Effect

Alhamid et al. [52] conducted an experiment on a solar-gas fired absorption refrigeration system installed in a real tropical environment. The system consists of 181 m² solar collectors and a unique single/double-effect water/lithium bromide absorption chiller with a nominal cooling capacity of 239 kW. The absorption chiller's main heat supply came from hot water (75°C-90°C) produced by the solar collectors to the single-effect generator and was supported by a gas-fired burner at the double-effect high-temperature generator. The authors also developed a system control operation for the optimum and safe operation of such a hybrid refrigeration system. The field tests resulted in thermal and electrical COPs of around 0.9-1.1 and 4.5-5.5, respectively. The field test results demonstrate the feasibility of the implemented control strategy for the optimum and safe operation of the system in an Indonesian climate, with the possibility of adaptation to other similar Asian tropical climates.

Zhang et al. [53] proposed a novel 300kW dual-evaporation-temperature combined-effect absorption chiller for THIC air-conditioning systems. The chiller produces high-temperature (16–18 °C) and low-temperature (7 °C) chilled water with a thermal COP above 1, utilizing heat sources around 100–120 °C. The COP of the proposed chiller is 24.1% - 50.4% larger than that of the conventional single-effect absorption chiller under typical high-temperature cooling capacity ratios of 0.5–0.7. The proposed system has a greater energy-saving potential in air-conditioned spaces with a large RSHR and fresh air ratio, achieving a thermal ESR and heating fluid saving rate over 20% under typical RSHRs of 0.6–0.8. Additionally, the system achieves an average ESR of around 30% under a wide range of ambient conditions, providing a novel solution for efficient and environmentally friendly THIC AC using solar energy or waste heat especially in the temperature range of around 100–120 °C.

Xu Z and Wang R [54] proposed a variable effect absorption cycle to address the instability of solar power in solar absorption refrigeration systems. ANN-based model of a variable effect LiBr-water absorption chiller developed using 450 groups of experimental data and then built a CPC driving absorption refrigeration system using the chiller model in TRNSYS program. The results showed that the variable effect chiller could operate with a low driving temperature, enabling a long working period, and had a high COP under high driving temperature, ensuring a competitive overall efficiency. The average chiller COP of 0.88 and solar COP of 0.35 were obtained. The study also analyzed the effects of solar collector area, storage tank volume, and cut-off driving temperature on system performance, and determined the optimal solar collector area and tank volume.

Cimsit C [55] designed a serial flow double effect absorption-vapour compression cascade cycle to enhance the performance of the absorption chiller and reduce the compressor work. A detailed thermodynamic analysis was conducted on the refrigeration cycle, which used R-134a for the vapour compression section and LiBr-H_2O for the absorption section. The results showed that the novel cycle's electrical energy consumption was 73% lower than the one-stage vapour compression refrigeration cycle, and its thermal energy consumption in the cascade cycle was 38% lower than the single-effect absorption-vapour compression cascade refrigeration cycle. Additionally, the cooling set and the LPG exhibited minimum and maximum exergy efficiencies of 21.85% and 99.58%, respectively with total cooling capacity of 300kW.

Li et al [56] investigated the thermodynamics of a novel solar refrigeration system, the SASCHCS for large buildings with multiple floors. A thermodynamic model was developed, and the performance of the hybrid system was analyzed in detail for various nominal cooling capacities of the absorption subsystem and storage tank volumes. The results indicated that the system's performance initially improves but then gradually decreases with an increase in the nominal cooling capacity of the absorption subsystem. The appropriate ratio of the nominal cooling capacity of the absorption subsystem to the collector area is suggested to be between 0.148 kW/m2 and 0.222 kW/m2. The optimal volume of the storage tank and rated cooling capacity of the absorption subsystem are 1.2m^3 and 50kW, respectively. The highest energy-saving fraction and COP of the hybrid system are 0.0767 and 4.741, respectively.

Yu et al [57] carried out an experimental of SASCHCS as a cost-effective solution for high-rise buildings. The prototype was developed and the performance was measured under various conditions in subtropical area using a 27 m2 stationary compound parabolic collector. The results showed that the absorption subsystem, driven exclusively by solar energy, can generate subcooling power for the compression subsystem, enabling the use of low-grade solar energy with temperatures above 60 °C. The peak instantaneous cooling power and COP of the absorption subsystem were 4 kW and 0.69, respectively, while the daily mean solar COP on sunny days ranged from 0.13 to 0.21.

Hybrid effect cycles have opened up new design options and possibilities for engineering the components inside the chiller, including the ability to create both single and double-effect cycles which is summarized in Table 3. These cycles also enable the integration of gas-fired burners and the ability to vary the two effects in a single chiller to meet the cooling demands of different environments. These hybrid systems offer promising opportunities for experimental study, although they may encounter challenges such as the stability of solar irradiation and relatively high initial costs. Nonetheless, further research and development in this area hold potential for enhancing the efficiency and effectiveness of refrigeration systems. Overall, hybrid cycles have expanded the range of options available for designing and optimizing refrigeration systems.

Table 3 Hybrid Effect Performance

References	Combined	Method	COP
Alhamid et al. [52]	Gas-fired burner	Experimental	0.9 - 1.1
Zhang et al. [53]	DETCE	Simulation	0.6 - 0.8
Xu Z and Wang R [54]	Variable Effect	Simulation	0.8 - 1.2
Cimsit C [55]	DEAVCR	Simulation	1.25
Li et al [56]	SASCHCS	Simulation	0.65 - 0.95
Yu et al [57]	SASCHCS	Experimental	0.69

7 Conclusion

Solar energy is a promising source of energy because of its potential due to the reduction usage of non-renewable energy. As the demand for cooling increases, solar-powered cooling technologies are becoming increasingly promising. Thermally activated cooling systems are being used all over the world for domestic and industrial cooling, alongside photovoltaic systems. Solar thermal cooling systems are more suitable than traditional refrigeration systems because they use pollution-free working fluids (instead of chlorofluorocarbons) as refrigerants. Solar cooling systems can be used as stand-alone units or in conjunction with traditional air conditioning systems to improve indoor air quality in all types of buildings, including residential and commercial.

The technology updates of the solar-driven LiBr-H_2O refrigeration system and its various categories has been reviewed in this study. The most popular LiBr-H_2O systems currently under development are the single-effect and double-effect. Single-effect systems are preferred when the required cooling demand is not high, as they are smaller and require less space. Double-effect systems are used for higher cooling demands, but they require an additional heating source. In cases where solar radiation is limited, a half-effect cycle is a better option. This is because it can use a lower temperature generator to drive the cooling system. It is also the best option for integration with other systems, such as the Kalina cycle. Triple-effect systems have the highest COP and cooling capacity, but they do not triple the increment of COP and heat capacity compared to the solar-powered single-effect. This is probably why there has been less development on this cycle in the past 10 years.

Water-cooled absorption refrigeration is preferred by researchers because it is more efficient in hot climates due to high heat rejection, which leads to a higher COP. However, in areas with water scarcity, air-cooled absorption refrigeration is a better option. Recent developments have shown that air-cooled absorption refrigeration can achieve almost the same COP as water-cooled absorption refrigeration, and it requires less maintenance because it does not have a cooling tower. However, the noise generated by the fan is a consideration. Furthermore, Geothermal heat rejection with very low pressure drops can save the auxiliary energy compared to the best case with wet cooling tower.

Hybrid effect cycles offer numerous advantages for refrigeration systems, particularly in tropical environments. With the use of solar-gas fired absorption systems, thermal and electrical COPs can be achieved in the range of 0.9-1.1 and 4.5-5.5, respectively. Advanced technologies such as DETCE absorption chillers, variable effect absorption cycles, and serial flow double-effect absorption-vapour compression cascade cycles can provide even greater energy efficiency, offer an environmentally-friendly and cost-effective solution for large buildings with multiple floors.

The deployment of large-scale solar-driven refrigeration systems is contingent on the availability of effective thermal storage technologies that can mitigate the effects of instability and intermittency over time. As such, long-term thermal storage solutions with high energy density are crucial for achieving continuous operation, improving reliability, and optimizing the energy efficiency and economic performance of solar-driven refrigeration systems. In larger buildings, solar cooling systems are often integrated with conventional air or water-cooled air-conditioning systems, and it is recommended to utilize the existing conventional cooling systems as auxiliary energy systems to simplify integration and facilitate control. Furthermore, establishing an optimal operational control strategy is highly recommended to enable seamless switching between solar cooling and auxiliary energy systems.

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9 Nomenclature

Abbreviation

AC	=	Air conditioning
ANN	=	Artificial neural network
COP	=	Coefficient of performance
CPC	=	Compound parabolic collector
CPV	=	Concentrating photovoltaic
DASC	=	Double-acting solar collector
DEAC	=	Double-effect absorption cycle
DEAVR	=	Double-effect absorption-vapour compression cascade
DETCE	=	Dual-evaporation-temperature combined effect
ECOP	=	Electrical coefficient of performance
EES	=	Engineering equation solver
ESR	=	Energy saving rate
GMDH	=	Genetic algorithm and group method of data handling
HEX	=	Heat exchanger
HEXH	=	Heat exchanger in high stage
HEXL	=	Heat exchanger in low stage
HPG	=	High pressure generator
HT	=	High temperature
LPG	=	Low pressure generator
MPG	=	Mid pressure generator
PEMFC	=	Proton exchange membrane fuel cell
PTC	=	Parabolic trough collector
PV	=	Photovoltaic
RSHR	=	Room sensible heat ratio
SASCHCS	=	Solar absorption-subcooled compression hybrid refrigeration system
SEAC	=	Single-effect absorption cycle

THIC	=	Temperature and humidity independent control
TRNSYS	=	Transient system simulation

Nomenclature

$\dot{Q}$	=	Thermal energy rate

Subscripts

a	=	Absorber
c	=	Condenser
e	=	Evaporator
g	=	Generator
H	=	High pressure
L	=	Low pressure
H_2O	=	Oxygen hydride (water)
LiBr	=	Lithium bromide
NH_3	=	Ammonia
[mmim][DMP]	=	1,3-dimethylimidazolium dimethylphosphate
th	=	Thermal

10 References

[1] IEA, Electricity Information Overview, https://www.iea.org/reports/electricity-information-overview, accessed March 15, 2023, 2021.

[2] IEA, Energy Statistics Data Browser, https://www.iea.org/data-and-statistics/data-tools/energy-statistics-data-browser, accessed March 15, 2023, 2022. IEA, Electricity Information Overview

[3] Reksowardojo, I.K., Ardiansyah, A., Leonardo, T.M., Permatasari, D., Indartono, Y.S., Ghany, F.A., *Study of an Indirect Injection (IDI) Diesel Engine Using Pure Coconut Oil, Pure Tamanu Oil and B-20 for Smart Microgrid Applications Part II: Pilot Testing*, Mesin, **29**(1), pp. 32–44, 2023.

[4] Reksowardojo, I.K., Ardiansyah, A., Leonardo, T.M., Permatasari, D., Indartono, Y.S., Ghany, F.A., *Study of an Indirect Injection Diesel Engine Using Pure Coconut Oil, Pure Tamanu Oil and B-20 as Fuel for Smart Microgrid Applications. Part I: Laboratory Testing*, Mesin, **29**(1), pp. 16–33, 2023.

[5] IEA, Renewables 2022, https://www.iea.org/reports/renewables-2022, accessed March 15, 2023, 2022.

[6] IEA, The Future of Cooling, https://www.iea.org/reports/the-future-of-cooling, accessed March 15, 2023, 2018.

[7] IEA, Space Cooling, https://www.iea.org/reports/space-cooling, accessed March 15, 2023, 2022.

[8] IEA, Greenhouse Gas Emissions from Energy Data Explorer, https://www.iea.org/data-and-statistics/data-tools/greenhouse-gas-emissions-from-energy-data-explorer, accessed March 15, 2023, 2021.

[9] Montagnino, F.M., *Solar Cooling Technologies. Design, Application and Performance of Existing Projects*, Solar Energy, **154**, pp. 144–157, 2017.

[10] Ibrahim, N.I., Al-Sulaiman, F.A., Ani, F.N., *Solar Absorption Systems with Integrated Absorption Energy Storage–A Review*, Renewable and Sustainable Energy Reviews, **82**, pp. 1602–1610, 2018.

[11] Ebrahimnataj Tiji, A., Ramiar, A., Ebrahimnataj, M., *Comparison the Start-up Time of the Key Parameters of Aqua-ammonia and Water–lithium Bromide Absorption Chiller (AC) under Different Heat Exchanger Configurations*, SN Applied Sciences, **2**(9), 2020.

[12] Chua, H.T., Toh, H.K., Malek, A., Ng, K.C., Srinivasan, K., *A General Thermodynamic Framework for Understanding the Behaviour of Absorption Chillers*, International Journal of Refrigeration, **23**(9), pp. 491–507, 2000.

[13] Lee, S.-F., Sherif, S.A., *Thermodynamic Analysis of a Lithium Bromide/Water Absorption System for Cooling and Heating Applications*, International Journal of Energy Research, **25**(11), pp. 1019–1031, 2001.

[14] Somers, C., Mortazavi, A., Hwang, Y., Radermacher, R., Rodgers, P., Al-Hashimi,S., *Modeling Water/Lithium Bromide Absorption Chillers in ASPEN Plus*, Applied Energy, **88**(11), pp. 4197–4205, 2011.

[15] R. & E, A.-C., *American Society of Heating*, ASHRAE Handbook Fundamentals, 2021.

[16] Kurosawa, S., Yoshikawa, M., *The Highest Efficiency Gas Direct-Fired Absorption Water Heater-Chiller*, pp. 88–112, 1982.

[17] Wilkinson, W.H., *What Are the Performance Limits for Double Effect Absorption Cycles?*, pp. 2429–2441, 1987.

[18] Herold, K.E., Radermacher, R., Klein, S.A., *Absorption Chillers and Heat Pumps*, 2016.

[19] Kujak, S., Schultz, K., *Demonstration of a Direct-Fired Triple-Effect Absorption Chiller*, Energy Eng, **97**(3), pp. 49–56, 2000.

[20] Yabase, H., Kawabata, K., Yakushiji, F., Takigawa, T., *Development of Triple-Effect Absorption Chiller-Heater*, pp. 1–8, 2005.

[21] Yabase, H., Makita, K., *Steam Driven Triple Effect Absorption Solar Refrigeration System*, 2012.

[22] S, J., R.Z, W., *Experimental Research on Characteristics of Corrosion-Resisting Nickel Alloy Tube Used in Triple-Effect LiBr/H_2O Absorption Chiller*, Appl. Therm. Eng, **21**(1), pp. 1161–1173, 2001.

[23] Georg, A., Reinhard, R., *Heat Conversion Systems*, CRC Press, Florida, 1994.

[24] Gao, J.T., Xu, Z.Y., Wang, R.Z., *Experimental Study on a Double-Stage Absorption Solar Thermal Storage System with Enhanced Energy Storage Density*, Applied Energy, **262**, 2020.

[25] Chen, J.F., Dai, Y.J., Wang, H.B., Wang, R.Z., *Experimental Investigation on a Novel Air-Cooled Single Effect LiBr-H_2O Absorption Chiller with Adiabatic Flash Evaporator and Adiabatic Absorber for Residential Application,* Solar Energy, **159**, pp. 579–587, 2018.

[26] Chen, J.F., Dai, Y.J., Wang, R.Z., *Experimental and Analytical Study on an Air-Cooled Single Effect LiBr-H_2O Absorption Chiller Driven by Evacuated Glass Tube Solar Collector for Cooling Application in Residential Buildings*, Solar Energy, **151**, pp. 110–118, 2017.

[27] Ha, Q.P., Vakiloroaya, V., *A New Single-Effect Hot-Water Absorption Chiller Air Conditioner using Solar Energy*, Solar Energy, 2013.

[28] Beausoleil-Morrison, I., Johnson, G., Kemery, B.P., *The Experimental Characterization of a Lithium Bromide-Water Absorption Chiller and The Development of a Calibrated Model*, Solar Energy, **122**, pp. 368–381, 2015.

[29] Li, M., Xu, C., Hassanien, R.H.E., Xu, Y., Zhuang, B., *Experimental Investigation on the Performance of a Solar Powered Lithium Bromide–Water Absorption Cooling System*, International Journal of Refrigeration, **71**, pp. 46–59, 2016.

[30] Marashli, A., Alfanatseh, E., Shalby, M., Gomaa, M.R., *Modelling Single-Effect of Lithium Bromide-Water (Libr-H_2O) Driven by an Evacuated Solar Tube Collector in Ma'an City (Jordan) Case Study,* Case Studies in Thermal Engineering, **37**, 2022.

[31] Sharifi, S., Nozad Heravi, F., Shirmohammadi, R., Ghasempour, R., Petrakopoulou, F., Romeo, L.M., *Comprehensive Thermodynamic and Operational Optimization of a Solar-Assisted LiBr/water Absorption Refrigeration System*, Energy Reports, **6**, pp. 2309–2323, 2020.

[32] Bellos, E., Tzivanidis, C., Symeou, C., Antonopoulos, K.A., *Energetic, Exergetic and Financial Evaluation of a Solar Driven Absorption Chiller – A Dynamic Approach*, Energy Conversion and Management, **137**, pp. 34–48, 2017.

[33] Hu, Y., Zhang, L., Zhang, H., Lv, H., Xu, C., *Thermodynamic Analysis of a Spectral-Splitting Hybrid PV-Thermal System with LiBr/H_2O Absorption Heat Transformer*, Energy Conversion and Management, **249**, 2021.

[34] Basu, D.N., Ganguly, A., *Solar Thermal-Photovoltaic Powered Potato Cold Storage - Conceptual Design and Performance Analyses,* Applied Energy, **165**, pp. 308–317, 2016.

[35] Liu, M., Cheng, Y., Cheng, W., Zhan, C., *Dynamic Performance Analysis Of a Solar Driving Absorption Chiller Integrated with Absorption Thermal Energy Storage,* Energy Conversion and Management, **247**, 2021.

[36] Camara, S., Sulin, A.B., *Study of a Double-Acting Solar Collector for Use in The Absorption Cooling System in Hot Regions,* Thermal Science and Engineering Progress, **31**, 2022.

[37] Li, Z., Ye, X., Liu, J., *Performance Analysis of Solar Air Cooled Double Effect Libr/H_2O Absorption Cooling System in Subtropical City,* Energy Conversion and Management, **85**, pp. 302–312, 2014.

[38] Lu, Z.S., Wang, R.Z., *Experimental Performance Investigation of Small Solar Air-Conditioning Systems with Different Kinds of Collectors and Chillers,* Solar Energy, **110**, pp. 7–14, 2014.

[39] Soussi, M., Balghouthi, M., Guizani, A., Bouden, C., *Model Performance Assessment and Experimental Analysis of a Solar Assisted Cooling System,* Solar Energy, **143**, pp. 43–62, 2017.

[40] Rossetti, A., Paci, E., Alimonti, G., *Experimental Analysis of the Performance of a Medium Temperature Solar Cooling Plant,* International Journal of Refrigeration, **80**, pp. 264–273, 2017.

[41] Hang, Y., Qu, M., Winston, R., Jiang, L., Widyolar, B., Poiry,H., *Experimental Based Energy Performance Analysis and Life Cycle Assessment for Solar Absorption Cooling System at University of Californian, Merced,* Energy and Buildings, **82**, pp. 746–757, 2014.

[42] De, R.K., Ganguly, A., *Performance Comparison of Solar-Driven Single and Double-Effect Libr-Water Vapor Absorption System Based Cold Storage*, Thermal Science and Engineering Progress, **17**, 2020.

[43] Ibrahim, N.I., Rehman, S., Al-Sulaiman, F.A., Ani, F.N., *A Systematic Thermodynamic Performance Assessment of a Solar-Driven Double-Effect Absorption Chiller Integrated with Absorption Energy Storage*, Applied Thermal Engineering, **221**, 2023.

[44] Ibrahim, N.I., Al-Sulaiman, F.A., Saat, A., Rehman, S., Ani, F.N., *Charging and Discharging Characteristics of Absorption Energy Storage Integrated with a Solar Driven Double-Effect Absorption Chiller for Air Conditioning Applications*, Journal of Energy Storage, **29,** 2020.

[45] Ferwati, M.S., Ahmad, A.M., Takalkar, G.D., Bicer, Y., *Energy and Exergy Analysis of Parallel Flow Double Effect H_2O-[Mmim][DMP] Absorption Refrigeration System for Solar Powered District Cooling,* Case Studies in Thermal Engineering, **28**, 2021.

[46] Ibrahim, N.I., Al-Sulaiman, F.A., Ani, F.N., *A Detailed Parametric Study of a Solar Driven Double-Effect Absorption Chiller Under Various Solar Radiation Data*, Journal of Cleaner Production, **251**, 2020.

[47] Marcos, J.D., Izquierdo, M., Palacios, E., *New Method for COP Optimization in Water- and Air-Cooled Single and Double Effect Libr-Water Absorption Machines,* pp. 1348–1359, 2011.

[48] Volpato, G., Rech, S., Lazzaretto, A., Roumpedakis, T.C., Karellas, S., Frangopoulos, C.A., *Conceptual Development and Optimization of the Main Absorption Systems Configurations,* Renewable Energy, **182**, pp. 685–701, 2022.

[49] Liu, W., Sun, B., Lai, Y., Yu, Z., Xie, N., *Performance Improvement of an Integrated System With High-Temperature PEMFC, Kalina Cycle and Concentrating Photovoltaic (CPV) for Low Temperature Heat Recovery*, Applied Thermal Engineering, **220**, 2023.

[50] Sun, F., Zhao, X., Hao, B., *Novel Solar-Driven Low Temperature District Heating and Cooling System Based on Distributed Half-Effect Absorption Heat Pumps with Lithium Bromide*, Energy, **270**, 126884, 2023.

[51] Gogoi, T.K., Hazarika, P., *Comparative Assessment of Four Novel Solar Based Triple Effect Absorption Refrigeration Systems Integrated with Organic Rankine and Kalina Cycles*, Energy Conversion and Management, **226,** 2020.

[52] Alhamid, M.I., Coronas, A., Lubis, A., Ayou, D.S., Nasruddin, Saito, K., Yabase, H., *Operation Strategy of a Solar-Gas Fired Single/Double Effect Absorption Chiller for Space Cooling in Indonesia*, Applied Thermal Engineering, **178**, 2020.

[53] Zhang, F., Yin, Y., Cao, B., Wang,Y., *Performance Analysis of a Novel Dual-Evaporation-Temperature Combined-Effect Absorption Chiller for Temperature and Humidity Independent Control Air-Conditioning*, Energy Conversion and Management, **273**, 116417, 2022.

[54] Xu, Z.Y., Wang, R.Z., *Simulation of Solar Cooling System Based on Variable Effect LiBr-water Absorption Chiller*, Renewable Energy, **113**, pp. 907–914, 2017.

[55] Cimsit, C., *Thermodynamic Performance Analysis of the Double Effect Absorption-vapour Compression Cascade Refrigeration Cycle*, Journal of Thermal Science and Technology, **13**(1), 2017.

[56] Li, Z., Jing, Y., J. Liu, J., *Thermodynamic Study of a Novel Solar LiBr/H_2O absorption chiller*, Energy and Buildings, **133**, pp. 565–576, 2016.

[57] Yu, J., Li, Z., Chen, E., Xu, Y., Chen, H., Wang, L., *Experimental Assessment of Solar Absorption-Subcooled Compression Hybrid Cooling System*, Solar Energy, **185**, pp. 245–254, 2019.