

Advancements in Solar-Assisted Cooling Systems: A Sustainable Solution for Energy Efficiency

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Abstract

Energy security denotes the capacity of a country to provide energy resources essential for its well-being at an affordable price. According to Rashid et al. (2023), energy availability is a proxy for a nation's standard of living and a key aspect of its economic development and technical progress. Currently, 75% of global Energy originates from burning fossil fuels, an activity that leads to the emission of greenhouse gases. Around 770 million of the world's population still lack electricity access, especially in Africa and Asia. For instance, in Bangladesh alone, despite 94.1 % of the urban population being connected to electricity, 60% of the consumers still face low voltage supply and load shedding (Rashid et al., 2023). The absence of electricity in remote areas has resulted in significant challenges to using conventional electrical devices like refrigerators, adversely affecting the inhabitants' living standards and economic prospects. Therefore, to counter this problem, renewable sources of Energy have become a viable alternative to traditional sources of Energy due to their capacity to help minimize the dependency on fossil fuels and contribute significantly to a country's energy security. This is why extensive Research into solar cooling systems has continually gained the limelight. This study examines the advancements in solar-assisted cooling systems and evaluates their benefits in enhancing energy efficiency and sustainability. The methodology guiding this Research is structured around equipment specifications, data collection protocols, and performance evaluation metrics to ensure a thorough analysis of energy efficiency and sustainability.

Keywords: Solar Cooling, Energy Efficiency, Renewable Energy, Absorption Chillers, Adsorption Chillers, vapor compression refrigeration (VCR), cooling load demands, Sustainable Energy.

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I. Introduction

Any nation's economic growth and development primarily depend on the presence of Energy. Energy security denotes the capacity of a country to provide energy resources essential for its well-being at affordable prices. Solar cooling systems are critical in modern society, serving residential, industrial, and commercial settings (Saha and Malek, 2024). In residential spaces, they ensure thermal comfort, particularly in regions with extreme temperatures, improving living standards. Within industries, cooling systems support the safe operation of machinery and preservation of temperature-sensitive materials, while commercial establishments utilize them to create conducive environments for employees and customers. Despite their importance, conventional cooling systems pose significant Energy and environmental challenges.

Firstly, traditional cooling technologies rely heavily on electricity, often derived from fossil fuels, contributing substantially to greenhouse gas emissions. Ali et al. (2024) submit that the increasing global demand for cooling, driven by urbanization, population growth, and rising temperatures, exacerbates the strain on energy resources. Furthermore, conventional systems usually utilize

refrigerants endowed with high global warming potential (GWP), thus intensifying their environmental impact. As such, these challenges underline the necessity for sustainable and energy-efficient cooling solutions to balance societal demands with ecological preservation.

Research Problem

The reliance on energy-intensive and environmentally detrimental conventional cooling systems is unsustainable. This concern calls for innovative solutions that address energy efficiency and environmental anxieties while meeting the growing cooling demand. Solar-assisted cooling systems that leverage renewable energy sources emerge as a promising alternative. Nonetheless, adopting these systems still faces technical, economic, and infrastructural barriers that necessitate in-depth Research and development.

Objective

This study examines the advancements in solar-assisted cooling systems and evaluates their benefits in enhancing energy efficiency and sustainability.

The paper begins with a literature review that explores existing technologies and innovations in

solar-assisted cooling systems. The methodology section outlines the research design and analytical framework used to assess these systems as the Results present key findings on performance efficiency and environmental impact. The discussion section, on the other hand, addresses potential barriers and opportunities for adoption. Recommendations offer actionable insights for stakeholders to promote solar cooling technologies. In the conclusion section, the paper summarizes findings and suggestions for future Research. However, it is critical to remember that the motivation behind this Research is to contribute to the growing body of knowledge on sustainable cooling solutions and provide practical pathways for integrating solar-assisted systems into mainstream applications.

II. Literature Review

The contemporary technology in energy sustainability highlights four distinct methods to achieve a solar cooling system: a PV-based solar energy system, solar-thermo-mechanical cooling system, Solar TEC, and solar thermal cooling. Conventional cooling systems, such as vapor compression refrigeration (VCR) and air conditioning units, dominate residential, commercial, and industrial applications. While effective, these systems are notoriously energy-intensive due to their significant electricity demand, especially within peak summer months of industrial activities. According to the International Energy Agency (IEA), cooling accounts for nearly 20% of global electricity use in

buildings (Citaristi, 2022). Additionally, using hydrofluorocarbon (HFC) refrigerants in conventional systems aggravates their environmental impact due to their high global warming potential (GWP). As such, the dependency on fossil fuel-based electricity and environmentally harmful refrigerants accentuates the need for sustainable alternatives.

Solar-assisted cooling systems have emerged as an innovative solution. These systems utilize renewable solar Energy to power cooling processes, significantly reducing reliance on electricity and fossil fuels. The first solar cooling approach involves using a solar energy system, which converts solar energy radiations into electrical Energy and applies it to refrigeration like traditional methods (Alahmer & Ajib, 2020). Secondly, solar Energy is cooled via thermoelectric and converted into electric Energy. Consequently, another scientific approach of frequent use involves using a thermal refrigeration system involving a solar collector to directly heat the refrigerants through collector tubes instead of depending on solar electric power. Two prominent technologies in this domain are absorption chillers and adsorption chillers. According to Ibrahim et al. (2024), Absorption chillers use heat from solar collectors to drive a thermochemical process while replacing the traditional compressor mechanism. In contrast, adsorption chillers utilize solid desiccants, like silica gel, to adsorb refrigerants under specific pressure and temperature conditions. Unlike conventional systems, both technologies demonstrate lower energy consumption and zero refrigerant emissions.

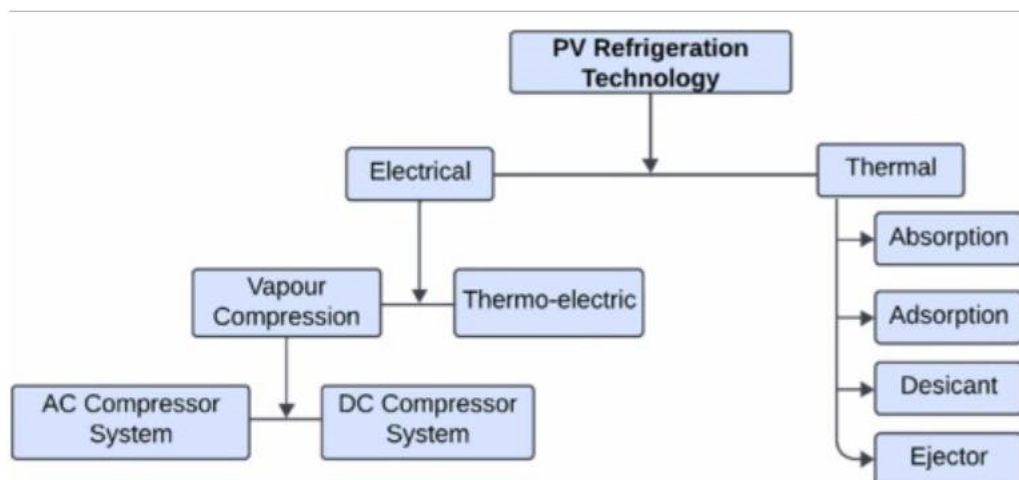


Fig 1. *Different cooling cycles coupled with PV.*

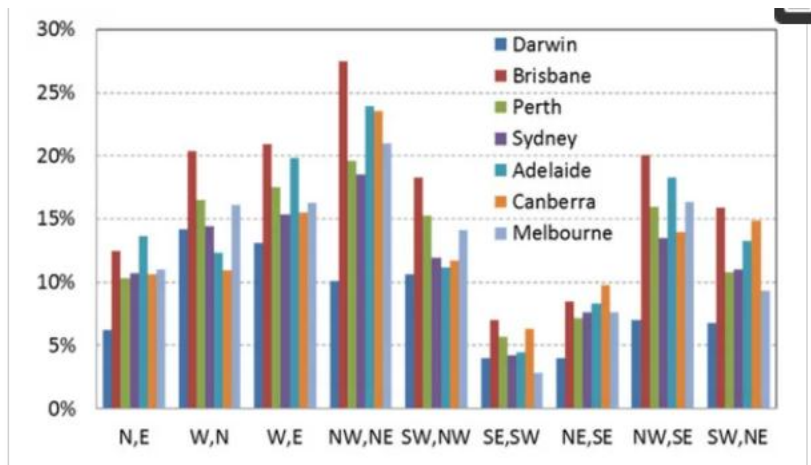


Fig 2. Orientation combinations affect the adsorption of chiller solar fraction

Research Developments

Recent studies have examined the performance and efficiency of solar-assisted cooling systems. A 2022 study by Aneli et al. evaluated absorption chillers in Mediterranean climates, finding that solar cooling systems achieved energy savings of up to 60% compared to conventional systems. Another study by Wang et al. (2020) explored hybrid solar-assisted cooling systems combining photovoltaic (PV) and thermal collectors, reporting improved efficiency and reduced system downtime, while the study by Alahmer and Ajib(2020) discovered the reliability of solar cooling systems in low-grade solar Energy of the construction industries. Advancements in materials, such as metal-organic frameworks (MOFs) for adsorption chillers, have enhanced their cooling capacity and operational range, as noted by Ibrahim et al. (2024). These advancements reduce energy consumption and lower greenhouse gas emissions, contributing to sustainability goals. However, scalability and economic feasibility remain challenges, limiting widespread adoption.

Research Gaps

Despite these promising developments, several critical areas require further investigation to enhance the viability of solar-assisted cooling technologies. As Anand et al. (2015) discovered, scalability is a primary concern because the current systems are usually tailored for small-scale or niche applications that limit their utility in large-scale commercial or industrial settings. As a result, Research on optimizing system design for diverse climatic conditions and cooling demands is essential.

Cost reduction is another pressing issue because Solar-assisted cooling systems typically involve high upfront expenditures from expensive components such as solar collectors and advanced refrigerants. Despite evident operational savings, the

long payback periods deter individuals from investing in these equipment. Even though Innovative financing models and government incentives could address these economic barriers, empirical evidence supporting their effectiveness is still limited. As such, their integration and reliability remain underexplored in most instances. Deye (2024) states that most solar-assisted cooling systems are standalone units, lacking seamless integration with existing infrastructure. For this reason, concerns regarding intermittent solar energy availability and maintenance complexities warrant further Research.

III. Methodology

This study aims to evaluate the performance of solar-assisted cooling systems using an experimental setup designed to simulate real-world applications. The methodology is structured around equipment specifications, data collection protocols, and performance evaluation metrics, ensuring a thorough analysis of energy efficiency and sustainability (Alghool et al., 2024). The equipment used in this study will include those that support solar collectors, cooling systems, and other crucial auxiliary tools. Flat Plate Collectors will be ideal tools for maximum sunlight collection in this Research owing to their affordability and effectiveness in low- to moderate-temperature operations.

To avoid associated expenditures from acquiring electricity-intensive compressors, cooling systems of absorption chillers coated with lithium bromide-water absorption chillers will utilize solar heat to drive the refrigeration cycle. Besides, an adsorption Chiller system of silica gel adsorbent will be integral to this study because of its capacity to leverage solid desiccant technology, which is ideal for improving energy efficiency and sustainability. Consequently, Auxiliary Equipment of Thermal storage tanks to store heat for continuous operation

during low solar radiance periods will be necessary as collective reservoirs. Pumps and controllers will be liable for regulating the flow of fluids while maintaining optimal system performance (Aneli et al., 2022). Sensors and data loggers must equally be used to monitor operational parameters in real time.

Data Collection

The experimental system will collect key operational parameters using advanced measuring instruments. For instance, Energy Consumption will be calculated using power meters to quantify electricity usage by pumps, controllers, and other auxiliary components. Solar Energy input, on the other hand, will rely on solar irradiance, and heat absorbed by the collectors will be recorded using pyrometers and thermal sensors (Rashid et al., 2023). The system's capacity to dispel optimum heat energy will be determined by measuring the working fluid's temperature difference and flow rate. The ratio of helpful cooling to input Energy will be calculated to assess the system's efficiency. However, the originality of data for this Research will only be guaranteed by organizing the data collection exercise for a period of three months, with each day involving the capture of daily variations in solar irradiance and cooling demand across diverse weather conditions.

Performance Metrics

The evaluation of solar-assisted cooling systems will focus on the Coefficient of Performance (COP), which will be calculated as the ratio of

cooling output to energy input. Energy Savings will be determined by comparing energy usage with a conventional cooling system under identical conditions (Ali et al., 2024). On the other hand, the experiment's cost-effectiveness will be analyzed through lifecycle cost assessments, operational expenses, installation timelines, and payback periods. To assess the ideal Environmental Impact of this experimental Research, the reduction in the volume of greenhouse gas emissions achieved through lower energy consumption and renewable energy use will be conducted every two weeks. By implementing these measures, the rationale of this methodology will ensure a robust analysis of the feasibility and sustainability of solar-assisted cooling systems. Still, it will also highlight their potential to revolutionize cooling technology.

IV. Results

Solar-assisted cooling systems significantly reduce energy consumption compared to conventional systems, intensifying it. Whereas traditional systems, such as fossil-fuel-powered heating and cooling, require large amounts of electricity or fuel derived from non-renewable sources, Solar-assisted systems leverage renewable solar Energy to supplement or entirely replace conventional energy inputs (Alghool et al., 2024). This, in turn, reduces dependency on grid electricity or fossil fuels.

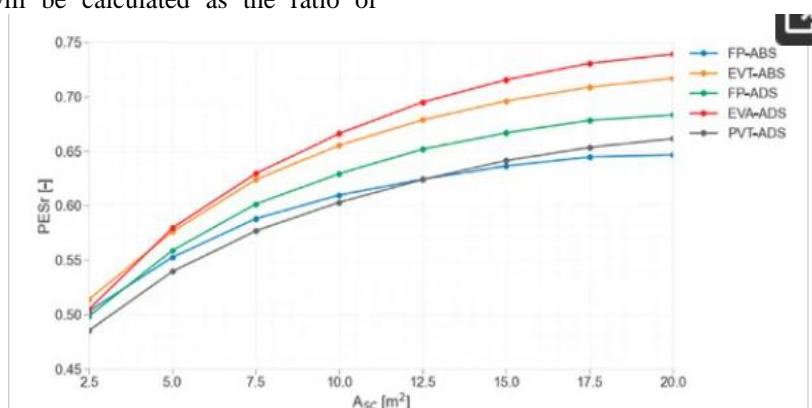


Fig. 3. Primary Energy saving ratio versus solar field collector area, parametric analysis.

Hybrid solar-assisted systems can reduce energy consumption by up to 50–70% for residential heating, cooling, and water heating. However, Photovoltaic (PV) systems with battery storage achieve near self-sufficiency in many regions with abundant sunlight, thus progressively lowering Energy drawn from the grid. No wonder Solar-assisted air conditioning units have been reliable in reducing operational energy use by up to 30%, especially in hot climates. According to Alahmer and

Ajib (2020), Switching from conventional to solar-assisted systems has profound environmental benefits, primarily through significant reductions in carbon emissions. Whereas Conventional energy production systems often rely on burning fossil fuels, which release greenhouse gases like CO₂, contributing to climate change, solar energy systems produce no direct emissions during operation (Anand et al., 2015). This is why large-scale implementation of solar-assisted systems in industrial and

commercial applications could reduce emissions by millions of tons per year globally.

Cost Analysis

Even though factors like equipment quality, permitting, and installation affect their initial expenditure, the financial analysis of solar-assisted systems reveals a trade-off between high initial costs and significant long-term savings. Citaristi (2022) observes that Solar PV systems typically have a higher upfront cost, averaging \$15,000–\$30,000 for residential installations, depending on system size and location. Solar thermal systems (for water heating or heating spaces) have lower initial costs, averaging \$3,000–\$8,000 for residential setups. Moreover, Solar systems offer substantial savings on energy bills, reducing annual energy costs by 50–90% in some cases. In addition, they attract minimal maintenance costs compared to conventional systems, as solar systems have fewer moving parts and long operational lifespans (typically 25–30 years). Even then, Incentives, such as tax credits and rebates, can reduce initial investment costs significantly, accelerating the return on investment (ROI). Regarding the cost-benefit assessment, the payback period for solar PV systems is typically 5–10 years, after which energy savings become pure financial gains. Over the lifespan of a system, homeowners can save tens of thousands of dollars compared to relying on conventional energy sources.

V. Discussion

The results underscore the transformative potential of solar-assisted systems in addressing Energy and environmental challenges. These systems reduce energy consumption by supplementing conventional power sources with renewable solar Energy, thereby decreasing reliance on fossil fuels and lowering carbon emissions. For instance, solar-assisted cooling systems leverage solar Energy for cooling load demands, offering up to 30% energy savings. This aligns with global sustainability goals, thus contributing to climate change mitigation through significant CO₂ reductions. The findings of this Research align with studies emphasizing energy efficiency and emission reductions from solar systems. Most Research publications consistently highlight 20–70% energy savings in residential applications. Still, differences emerge regarding implementation barriers, where some studies report higher feasibility in sunnier regions, while others note scalability in hybrid designs even in less sunny climates.

Challenges and Applicable Solutions

Since solar-assisted systems require substantial upfront investment and regular

maintenance that increases operational costs, they may deter widespread adoption. As highlighted by Deye (2024), the fact that their efficiency varies with solar irradiance is an indication that their efficiency may not be guaranteed in a cloudy or inconsistent climate. However, solutions to inconsistent solar-assisted cooling systems are available in various dimensions, such as integrating solar with conventional systems that safeguard its reliability even within environments with low solar availability. Secondly, innovative materials such as high-efficiency photovoltaic materials and energy storage technologies, such as perovskite solar cells and lithium-ion batteries, can improve performance and reduce costs (Saha & Malek, 2024). In addition, educating consumers on long-term savings and environmental benefits can drive acceptance and adoption of sustainable energy methodologies.

VI. Recommendation

To enhance solar cooling technologies and accelerate their adoption, a multi-pronged strategy of technological advancement and policy support and incentives are essential. For instance, investments in advanced solar materials, such as perovskite solar cells and multi-junction PVs, can significantly increase efficiency. Developing thermally efficient components for solar-assisted cooling systems, like advanced heat exchangers, would reduce energy losses. In contrast, integrating solar cooling with energy storage solutions, such as phase-change materials or thermal batteries, can ensure consistent performance in low sunlight conditions. Alahmer and Ajib (2020) posit that coupling solar cooling systems with smart grids can optimize energy use by dynamically managing demand and supply. Real-time data exchange between cooling systems and grids enables intelligent energy allocation, reducing waste and enhancing efficiency.

Secondly, it would be effective when Government policies are aligned to prioritize solar cooling adoption through subsidies, tax credits, and low-interest financing. For example, as suggested by Ibrahim al (2024), introducing grants for Research and development in solar cooling technologies will encourage innovation by mandating renewable energy integration in new construction projects, especially in commercial and industrial sectors. Despite the advancements in solar-assisted cooling systems as a sustainable solution for energy efficiency, further Research is needed to explore how hybrid systems, when combined with solar cooling of other renewable energy sources, could fuel the development of cost-effective energy storage. Furthermore, studies on system performance under varying climatic conditions are critical for broader adoption.

VII. Conclusion

This study evaluated the energy-saving potential, environmental impact, and cost-effectiveness of solar-assisted cooling systems compared to conventional systems. By analyzing energy consumption reductions, carbon emission offsets, and cost dynamics, the study highlighted the transformative role of solar cooling technologies in addressing global Energy and environmental challenges. Methodologically, the Research focused on comparing the performance of solar-assisted systems with traditional fossil-fuel-based systems, drawing insights from efficiency metrics, ecological benefits, and cost analyses. The findings revealed significant energy savings, with solar-assisted cooling systems reducing consumption by up to 30% and contributing to substantial reductions in carbon emissions. Despite higher initial costs, these systems offer long-term economic benefits through lower operational expenses and government incentives. However, barriers such as high capital requirements, maintenance challenges, and weather dependency were identified as obstacles to widespread adoption.

To overcome these challenges, the study recommended advancing solar materials, such as perovskite solar cells, and integrating solar cooling with innovative grid technologies to optimize performance. Policy support, including subsidies, tax credits, and renewable energy mandates, was emphasized to promote adoption.

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