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# Photovoltaic-Driven Cooling Systems: Advances, Challenges, and Future Directions

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**ABSTRACT**

This paper aims to reviewing the development and the prospects of the photovoltaic cooperating cooling systems. This topic covers the basics, new technologies, efficiency enhancement, and consequences of these systems in terms of environment and economy. The incorporation of photovoltaic (PV) technology into cooling system has also emerged widely for meeting the increasing demand for appropriate cooling methods especially in the regions that characterized by high temperatures. Photovoltaic air conditioning systems use electricity from solar power to support cooling processes, including vapor compression and absorption chillers with little or no inputs from fossil resources, thus reducing environmental effects. This paper provides a brief discussion of the various topologies of these systems; systems that incorporate DC compressor units, as well as solar-only systems that incorporate electric chillers and solar thermal systems. These designs are best used and suited for different uses and are more versatile in terms of functionality. The paper also explains the difficulties that arise when trying to implement the photovoltaic cooling technologies: high costs of investment, low storage capacity, and problems with fine-tuning. However, the combinations of these obstacles do not preclude the opportunities of energy conservation and the decrease of greenhouse gas emissions. As the final discussion of the paper, recommendations on future research and development are made with regard to the integration and control, cost effective measures and cooling technologies for enhancing the effectiveness of photovoltaic-driven cooling systems.

## 1. Introduction

### *1.1. Overview of Photovoltaic-Driven Cooling Systems*

Photovoltaic-cooling systems are systems that are powered by solar in their effort to provide enhanced and eco-friendly cooling solutions. These systems use PV technology to convert sunlight into electricity in order to drive cooling processes such as vapor compression and absorption chillers. One benefit is that they are less dependent on fossil fuels, thus fixing a major issue of power conservation in the increasing incidences of heat around the globe.

New cooling methods are needed when temperatures are high, especially in hot areas where heat and energy are a problem. One of the prospective approaches to applying PV technology is its integration with cooling systems. Some of the configurations include, small-scale unit retrofitted with direct current compressors, hybrid system incorporating solar thermal technologies and electric chiller. The freedom of design provided by this system enables client or location specific customization in responding to building requirements and climatic conditions to general effectiveness.

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A study shows that use of solar cooling technology goes a long way in reducing carbon footprints than conventional air conditioning systems. For instance, the applications such as solar powered absorption chillers have demonstrated a way of reducing CO2 emissions while at the same time affording long-term cost benefits from harnessing free solar energy.

Recent innovations in PV are as follows: Building Integrated Photovoltaic s (BIPV). It is a system where the photovoltaic components are incorporated into the building structures to make them more efficient in terms of space and architecture all in the process of producing energy. Nevertheless, there are still some concerns that may slow further adoption, including high initial cost of installation and expensive costs of maintenance. Another factor that affects system performance is weather conditions in the locality and the right sizing compared to the building parameters of the structure.

To advance these technologies, further research in the enhancement of the performance of the technologies as well as search for better financing models is imperative. It is further recommended that government polices increasing acceptance can increase adoption of renewable energy through incentives from households and commercial buildings. In summary, the utilization of cooling systems powered by photovoltaic is a sustainable avenue towards enhancing urban practice with the increasing temperatures [5], [2], [12], [11], [9] and [6].

### *1.2. Importance of the Study*

It is vital to investigate the potential of photovoltaic integration for cooling since its demand is expected to increase with the rising world temperatures and the progress in urban development. Conventional air conditioners are major players in greenhouse emissions, being estimated to be responsible for 20% of emissions associated with residential cooling in particular. With energy demand from these systems rising with time particularly in regions with high temperatures, incorporating renewable energy systems such as photovoltaic, PV offers a practical and effective solution for the reduction of energy effects on the environment.

Photovoltaic-driven cooling systems use solar energy, thereby reducing the need for fossil fuel and the associated carbon footprint of conventional cooling systems. While used as sources of energy, these systems can significantly reduce operating expenditure and emissions when compared to electric based systems. Which coincides with the peak cooling load, intensifies the benefits yielded by PV solutions even more.

Implementing these technologies is consistent with international and national environmental conservation strategies and plans towards efficiency of renewable energy in heating and cooling industries, for instance, EU’s annual target of at least 1.3%. The economic effectiveness of photovoltaic systems, helped by innovations that make solar technology cheaper, helps make them even more interesting.

Apart from environmental effects, they are capable of promoting of economic development by generating employment opportunities in renewable energy industries as well as contributing to development of technologies. If market acceptance grows and the number of installations rises, the capital costs could decrease due to reductions in the costs of production.

This study also shows that there are multiple specific uses of photovoltaic-driven cooling in different climates and building applications, enabling specific solutions to maximize performance and meet customer needs. Studying such systems helps to sustain power generation during the cloud coverage while optimizing the results at the same time. The funding of this technology caters for pressing indoor comfort concerns and helps in achieving climate change objectives through effective use of energy in cooling. Further study is required to improve and remove these systems and the constraints of adoption, including the initial capital costs and stakeholder awareness, [14], [29], [5], [12], [13], [18], [16] and [32].

**Table 1**: Non-exhaustive list of solar cooling/heating kits manufacturers, [29]

| Manufacturer (Country) | Product Name | Cooling capacity [$kW_c$] | Cooling Technology / working pair |
|---|---|---|---|
| Changzhou Recreate Electrical Appliances Technology Co., Ltd (China) | ACDC Hybrid Solar Air Conditioner VRF System | 2.6–7.0 | Conventional A/C technology |
| COLDINNOV (France) | FREECOLD | 2.6–3.5 | Conventional A/C technology |
| EDF Optimal Solutions (France) | Package system | 17.5–210 | Absorption ($LiBr–H_2O$) |

## 2. Fundamentals of PV-Driven Cooling Systems

### *2.1. Basic Principles of Photovoltaics*

Photovoltaic or PV system utilizes solar energy where photovoltaic cell is used to trap sun’s rays and transform light to electricity by photovoltaic effect that occurs on the semiconductor materials. It is therefore important to understand the basics of the PV systems because they form the core of photovoltaic driven cooling technologies. The PV system is built around solar cell, which is mostly made from silicon material. This cell captures light energy from the sun and thereby releases electrons that create an electric current. Depending on the specific application, one or more cells are connected in parallel to form a panel or modules that in turn will provide voltage and current output.

The performance of the PV cells is defined by how effectively the solar energy is converted to electrical energy; the modern and commercialized panels have an efficiency ranging from 15% to 22%. There are several parameters, which affect this efficiency – material, temperature, and intensity of light; for example, high temperature lowers the efficiency of the PV module. For even more enhancement of the conversion efficiency of solar cells, there is a study on the development of compound semiconductors referred to as tandem solar cells.

In photovoltaic–powered cooling systems, the electrical energy produced by the PV modules mostly drives conventional refrigeration mechanisms such as vapor compression. In these systems, the produced electricity switches on a compressor that blows refrigerant through evaporative and condensive coils that make the cooling. Traditional cooling solutions uses either fossil fuel or grid electricity unlike the PV-powered coolers that have limited use of non-renewable energy sources.

Another future research area relates to the use of photovoltaic-thermal (PVT) collectors which produce both electric power and heat for cooling purposes. This dual-output make it possible to optimise the utilisation of solar energy as compared to normal PV systems that are primarily concerned with power production. It is also pointed out that by using waste heat from electricity generation, PVT collectors can enhance the efficiencies of overall systems where waste heat can be used for other heating processes or even be utilized to drive thermally activated cooling cycles.

As well, integrating energy storage systems, which include batteries, with photovoltaic cooling systems guarantees power delivery during low irradiance or high cooling requirements. An important aspect is that management efforts are necessary to achieve the maximum results from system functioning under different environmental conditions. Studies show that complex controls could improve load-following capabilities and achieve near-optimal solar-resource utilization efficiency.

Incorporation of smart technologies makes it possible to monitor these systems and make necessary adjustments once the temperature drops or increases or once the levels of solar radiation differ. These innovations boost responsiveness and operation effectiveness and increase the acceptance of renewable-based cooling solutions.

Thus, knowing the fundamentals of photovoltaics is crucial to the application of photocell-driven cooling technologies that harness renewable energy in minimizing the effects of conventional cooling on the environment, [31], [1], [36], [11], [37] and [8].

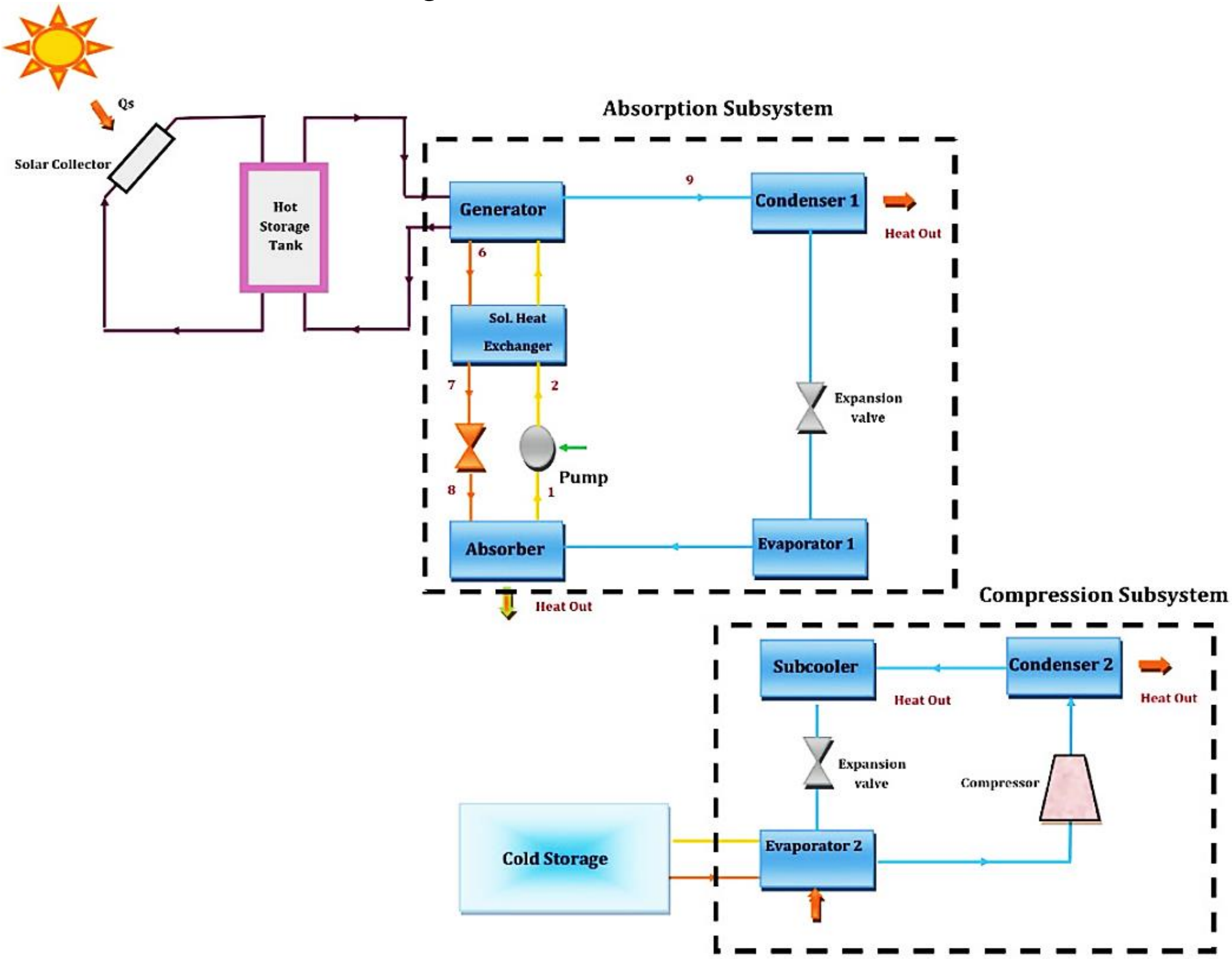


**Figure 1.** Solar operated absorption-compression hybrid system, [27]

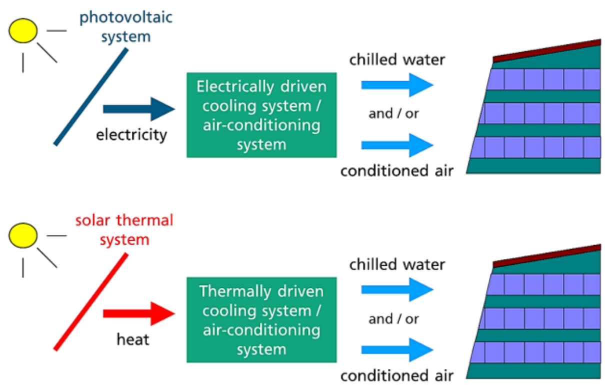


**Figure 2.** Principles for solar driven cooling, [8]

*2.2 Mechanisms of Cooling Systems*

Photovoltaic cooling systems are cooling systems that use electricity from solar energy to drive various cooling technologies. Most of these systems use photovoltaic or PV cells for conversion of sunlight into electricity and the source is available in unlimited fashion. The produced power could be used in various cooling processes such as vapor compression chillers, absorption chillers, and adsorption cooling.

VC chillers are frequently employed in PV-cooling, mainly because they they are highly effective heat exchangers. In such configurations, electricity produced from the PV module is used to operate a compressor, which blows refrigerant through evaporator and condenser coils. When the refrigerant is in the evaporator coil it turns to gas and the heat from the environment or indoor air is removed cooling the room. This operation is frequently accompanied by thermally promoting operations that use solar thermal energy together with electric power.

Another cooling technique used by absorption chillers is through thermal and electrical energy interconnection. In these systems, a liquid absorbent absorbs a refrigerant; when heated through solar thermal collectors or waste heat recovery, the refrigerant evaporate and cool when the pressure is applied. This dual-energy method greatly enhances the whole system efficiency and at the same time, the best usage of the available solar power.

A new innovative cooling technology known as adsorption cooling depends on the formation of gas-solid adsorption interactions for cold temperature generation. Like absorption techniques, adsorption chillers need heat input, although they can work well in lower temperature levels than most absorption systems. It makes them suitable for low temperature PV installations because the open circuit voltage can easily be kept low. Progress has been made on both technology of adsorbent and system design, which has led to better COP and other performance indicators.

Furthermore, development of multi-technology systems such as photovoltaic and concentrating solar power (CSP) are on the rise due to improved thermal coefficients. These hybrid configurations afford a great deal of flexibility in terms of the cooling requirements in addition to the further optimization of energy generation depending on the time of the day.

Further, new developments in high thermal conductivity coolants improve the heat exchanging capability within such systems by most compact designs with high thermal control capabilities. This improvement makes it easy to optimize and manage the space resource more in building applications besides achieving operational performance.

Apart from making use of photovoltaic power, architectural integration of photovoltaic-driven cooling technologies is a crucial step in reducing the dependence on fossil fuels for cooling. This can be illustrated by facade-integrated photovoltaic modules, which, in addition to providing the power plant function, make a significant use of building surfaces and improve aesthetic appeal in architectural settings.

Therefore, comprehension of these mechanisms enables sound design choices concerning the photovoltaic-driven cooling systems for various climatic conditions and specific operational profiles, [4], [5], [10], [2], [1], [3], and [6].

**Figure 3.** Autonomous working PV-driven split cooling device with 4.4 kW cooling power and DC chiller technology, [6]

## 3. Advances in Photovoltaic-Driven Cooling

### *3.1 Recent Technological Innovations*

New developments in photovoltaic systems for cooling have improved the way they operate and how they can be used. A significant enhancement is integrated control strategy for enhancing the efficiency of solar cooling systems which draw power directly from distributed PVs, and hence no batteries. This method involves the ability of changing the operation frequency of compressors with respect to the impedance of the photovoltaic (PV) array. Consequently, the average photoelectric conversion efficiency rises to around 12.9 percent, which is 83.7 percent higher than that of the conventional control solution. In addition, when compared to an ice thermal storage model, the system COP solar value was determined to be 0.263 an improvement of 60.4% from conventional systems.

Another innovative development of interest is the experimental study of the cooling systems as evaporative chimneys, where solar contribution is estimated to be 64.4% of the total energy used. These designs not only result in tens of thousands of primary energy use and CO2 emission savings, but also show the variable performance depending upon the climatic conditions, implying their flexibility.

There is also ongoing integration between the two solar applications, namely desalination and cooling, especially by incorporating novel materials such as reverse osmosis (RO) systems with adsorption chillers. Research shows that these hybrid configurations raise the freshwater production while boosting the efficiency of energy several times if driven by photovoltaic or photovoltaic-thermal collectors.

In addition, new scientific developments in thermoelectric cooling technologies have been identified as the next growth area of this industry. Among the benefits arising from solar thermoelectric cooling are the integrated design and very high reliability because the systems have no mechanical parts or fluids, thus making them applicable for domestic refrigeration and air conditioning.

In more recent studies, there has been examined more complex systems, including combined PVT modules that can both cool and heat water and generate hot water without the use of batteries. Due to this flexibility, this application is significant in using in some mobile conditions such as boats, for instance, it has a small space.

Altogether, these innovative creations are opening the path toward increasing stamina solutions that meet growing energy needs without causing harms usual to conventional refrigeration systems, [20], [11], [17], [23], and [19].

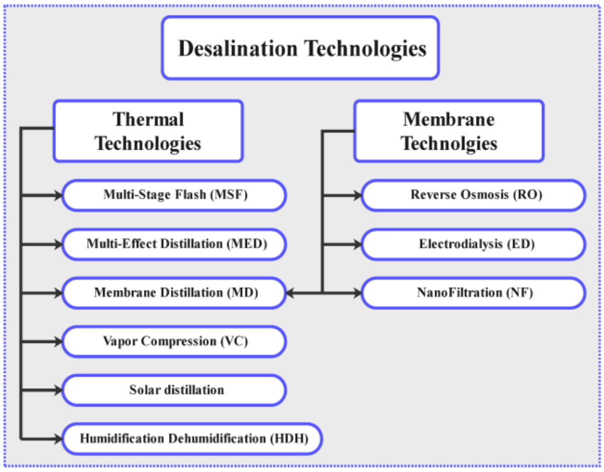


**Figure 4.** Main desalination technologies reported in the literature, [17]

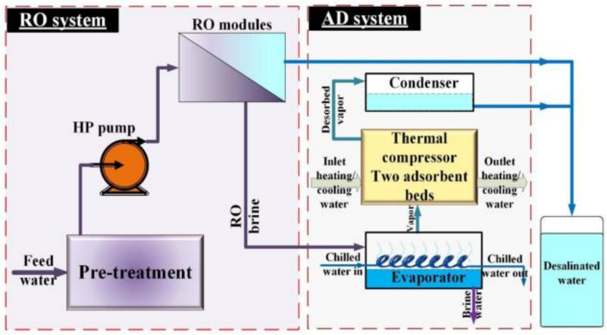


**Figure 5.** The RO-ADC system diagram, [17]

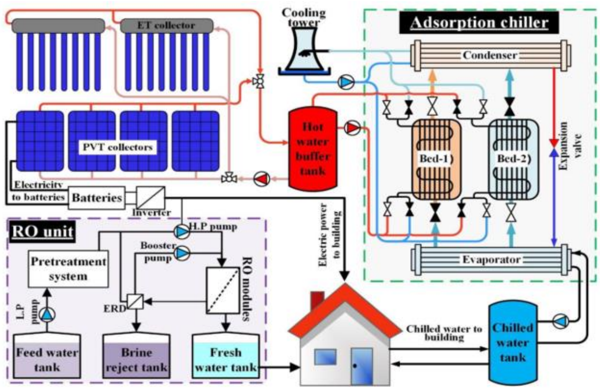


**Figure 6.** SROC system, [17]

*3.2 Case Studies and Success Stories*

Solar powered cooling systems are on the rise globally as being green technologies. One of the most important is the solar-powered absorption system at the Center for Renewable Energy Sources and Saving (CRES) in Athens, Greece, in exploitation since December 2011. This installation consists of a solar power plant of area 149.5 $m^2$, the flat plate collectors, and an energy storage system in the ground with a volume of 58$m^3$. The absorption chiller uses LiBr-H2O operating at a nominal capacity of 35 kW backed up by an 18-kW conventional heat pump. It has a solar fraction of nearly 70%; Total cooling energy required every year is 19.5 MWh from May to September and heating energy required is 12.3 MWH from October to April.

Further, new cooling system that combines the absorption/thermoelectric cooling system has been developed apart from that a concentrated photovoltaic/thermal system has also been designed to heat and cool at a time. This show how various technologies can be combined to enhance the use of energy.

Studies on photovoltaic-driven refrigerated warehouses suggest that various ice storage management can influence output in various ways, and pilot-scale systems based on actual data are more reliable than simulations than simulated systems.

Dynamic simulation models have also enhanced standalone photovoltaic driven drinking water fountain with battery storage as it has been observed in Bahia Brazil that through optimal design of three photovoltaic module and two batteries, the thermal efficiency has increased by more than one third as compared to the earlier design.

Research undertaken for the UAE showed that solar-powered district cooling systems for residential areas were significantly cheaper in terms of installation than conventional air conditioning; in fact, these costs could be up to 65 percent lower.

Furthermore, research in the new hybrid solar-driven desalination and cooling technologies is on the rise, making it possible to tackle water problems and climate change issues. In general, these innovations underscore the importance of photovoltaic-driven cooling systems in Sustainable Development and Minimisation of Impacts on the Environment, [4], [35], [17], [33], [18], [34] & [39].

## 4. Performance Optimization Techniques

### *4.1. Energy Efficiency Strategies*

Optimisation techniques applicable to photovoltaic-driven cooling systems to improve efficiency and curb operating costs are important. Integration of improved materials like new absorbents and ionic liquids increases heat and mass transfer in solar cooling structures. These advancements in materials science allow the design of systems that are more condensed but possess better thermal-to-thermal conversion ratios.

Another good way of increasing efficiency is by using photovoltaic-thermal (PVT) collectors. PVT systems produce both, electricity and heat from the same source of light, thus satisfying different energy requirements at once. This integration with their existing commercial absorption chillers optimizes heat management and the response to fluctuations in demand, resulting in a massive decrease in electricity usage while at the same time achieving greater penetration of renewable energy into cooling systems.

Optimization of system configurations by use of dynamic modelling methods enable the designer to estimate energy consumption rates and match the configuration of the system in use with the actual use requirements. There are simulation tools that incorporated the specific climatic conditions that apply in a certain area so that the sizing and placement of components will be more effective in their operation.

Adopting of smart control mechanisms with intelligent sensors and automation systems even enhances efficiency even further. These technologies control cooling in relation to variations in either ambient temperature or occupancy, enhancing comfort and minimizing wastage of energy.

Combined cooling, heating and power (CCHP) configurations and multi-generation systems can also enhance efficiency in which waste heat from power production is used for more cooling. Such circular energy use hence makes best use of resources in the electrical and thermal facets.

Last but not the least, the differentiation approach of utility rates in design and operation can produce additional optimization. Operations during peak pricing times mean that users get to save on electricity costs while getting most value out of the existing structures, [4], [28], [24], [2], [40], [38] and [41].

*4.2. Integration with Other Systems*

Utilizing photovoltaic for cooling systems offers a great potential to improve or increase the capacity efficiency of diverse energy frameworks. One of the emerging strategies is integration of photovoltaic (PV) and cold thermal energy storage (CTES) systems, where CTES enables the storage of cold energy created during peak PV hours. Solving the challenges of cooling demand and PV generation, it enhances the system's efficiency.

Other configuration of the cooling system such as adsorption chillers combined with vapor compression cycles are also used in the cooling system for photovoltaic. When there is high demand, or low level of sunlight, vapor compression can continue providing cold water while adsorption chillers can work at their optimum capacity. This leads to enhanced dependability, less emissions of green house gases, and lower product life costs.

The use of other forms of renewable energy sources alongside photovoltaic have other benefits. Intermittent systems that combine solar with wind or hydro give the required energy security and make the power output more predictable since the less external impacts on generation fluctuation due to climate change will occur.

For such systems, the monitoring and control mechanisms are sophisticated. Remote monitoring provides the real ability to monitor PV output and cooling efficiency at any time and make necessary adjustments. It is also possible to apply artificial intelligence and machine learning to increase the efficiency of operation since load demands may be predicted, and the system responses may be optimized.

Energy management strategies with the use of smart grids is also important. Integrating PV power generation with building energy demand through demand side management measures is economical in addition to supporting grid stability.

Finally, schematic designs that aim at effective heat control through passive means in combination with active solar systems can result in improved energy control. These strategies minimize a building's dependence on mechanical systems and optimize the amount of solar heat.

With the help of such integration strategies – incorporating PV technology with energy storage, hybrid systems, better monitoring, smart grid integration, and efficient designs – photovoltaic driven cooling systems can provide optimal cooling efficiency in addition to serving sustainability agendas [14], [28], [42], [8], [40] and [21].

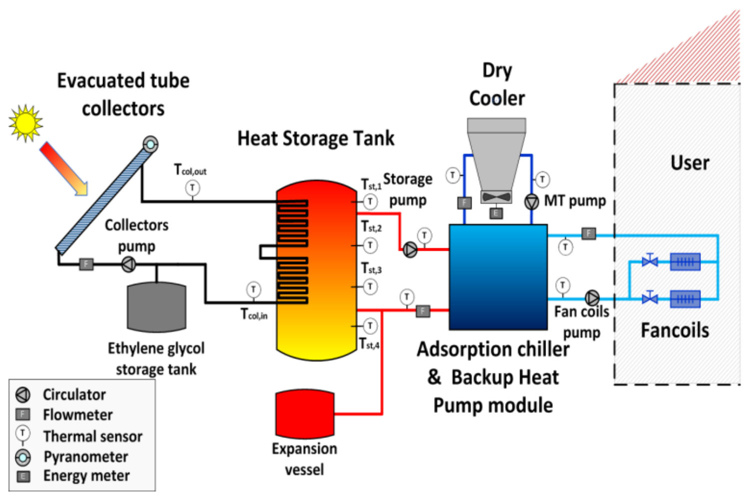


**Figure 7.** Schematic of system prototype with all the involved measuring devices, [42]

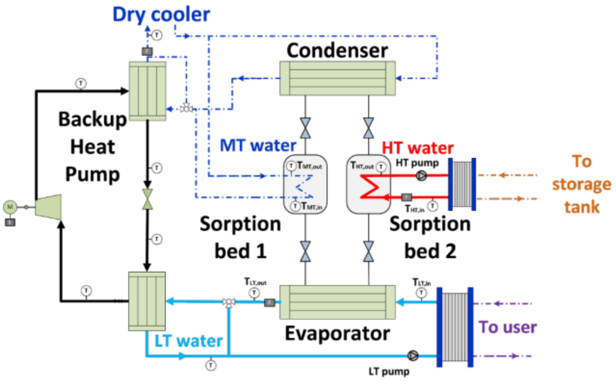


**Figure 8.** Detailed schematic of the hybrid adsorption chiller/backup heat pump module, [42]

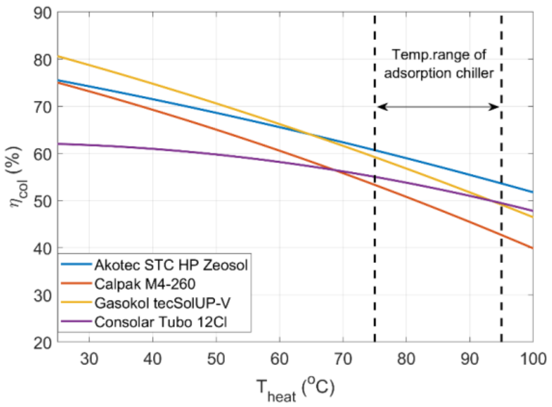


**Figure 9.** Performance curve of the developed solar collectors for ZEOSOL system (blue line) in comparison to other commercial solar collectors

The preliminary measuring of the proposed system was divided in three parts: It includes the following elements of the solar cooling system: (a) the experimental testing of the solar collectors and the storage tank, (b) the performance testing of the hybrid adsorption chiller and the dry cooler and the auxiliary equipment, namely the circulation pumps. The solar collectors applied in the system are heat pipe evacuated tube collectors by Akotec that are designed for ZEOSOL system and are capable to perform between 65-95 oC. The collectors involved in the research were certified by the ISO 9806 from a certified institute.

## 5. Challenges in PV-Driven Cooling Systems

### *5.1 Technical Limitations*

The three main technical barriers that affect photovoltaic driven cooling systems are as follows; One of the largest problems is the variability of solar energy production that does not correspond to cooling requirements, for example on a gray day. It means that the issue of energy storage is crucial, but existing battery systems may not be ready for long-term storage to cover this unpredictability without significant expenses.

The other concern is the effectiveness of the solar collectors. Traditional photovoltaic panels utilize a small slice of sunlight to create electricity and, therefore, restrict the viability of cooling systems with such energy. Innovative designs of collectors are intended to increase their efficiency; however, incorporating these technologies into existing systems often involves significant reconstruction and capital costs.

Heat rejection in these systems is also challenging; many of these systems' designs have issues with thermal management. This inefficiency can lead to excessive energy consumption by the auxiliary components of the plant such as pumps and fans. An adequate design of heat rejection subsystems is critical; their poor design results to low cooling and high operational cost.

This is made worse by the fact that complexity could also arise from the system integration. Most photovoltaic-driven cooling systems comprise a series of connected components that are best-regulated employing complex control techniques. As can be seen, this complexity can become problematic when attempting maintenance work and can introduce inefficiencies. He noted that this poses a significant challenge to technicians as it may prove very hard for them to diagnose a problem and this may lead to very many days of product downtimes and more expenses.

These technical limitations are however largely determined by economic factors. However, the tendency to install high initial capital can act as a barrier to use this technology because of the benefits it has in the end. Further work is required to improve the

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performance of cooling systems that are integrated with PV systems, with current ideas such as phase change materials providing potential for improvement if future work is conducted. These constraints explain why there is a continuous need to conduct research and development to enhance the feasibility of these technologies for further application. See references: For enhanced description, see [4], [13] and [27].

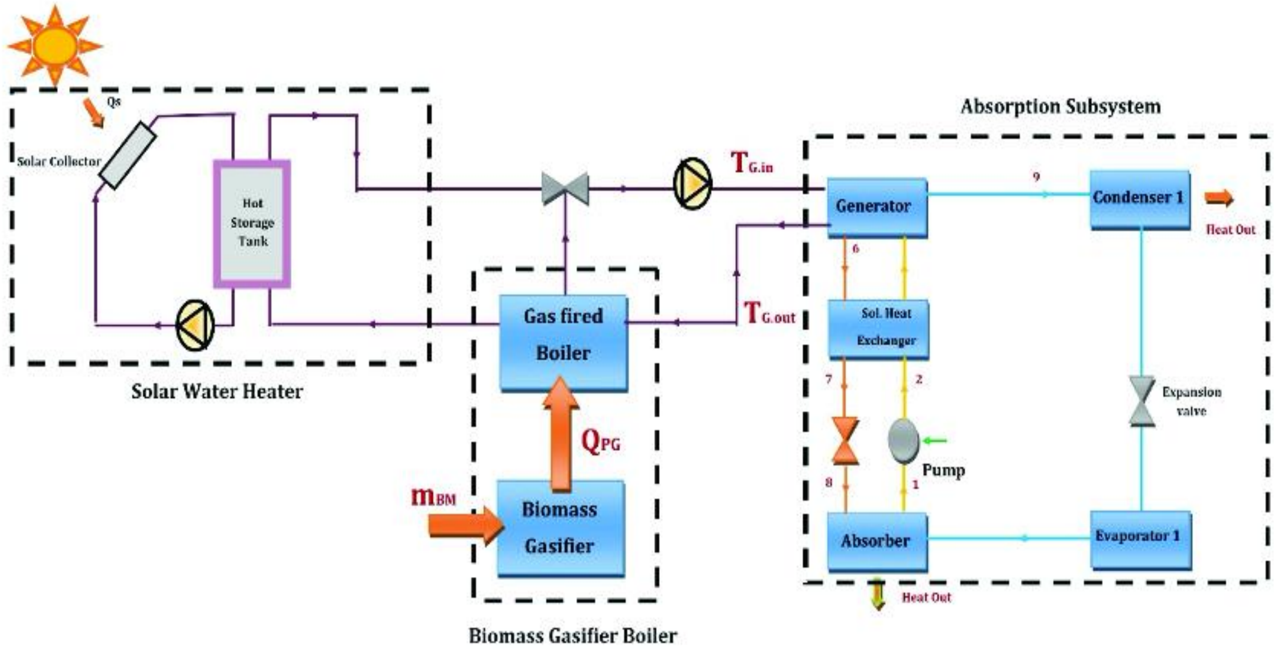


**Figure 10.** Solar biomass operated absorption-cooling system, [27]

*5.2 Economic Barriers to Adoption*

The relatively high cost, particularly the capital investment costs on photovoltaic driven cooling systems are one major factor that hinders the widespread use of these systems. While comparing with the conventional systems of cooling, it is essential to note that the use of PV-based solutions often requires a significantly larger initial capital to install solar collectors, storage tanks and other kinds of components. This high initial cost can be a put off to potential users even in residential places where there are cheaper options available. In addition, the market competition of these specific parts and components is relatively low which makes their prices rather high.

Another very important factor influencing the economic feasibility is the operational effectiveness of the project. According to many papers, the efficiency of most of the cooling systems powered by PV is lower compared to conventional benchmarks. While they may claim lower CO or, operation costs in the end, this can only be real if there has been a breakthrough in both energy storage and systems integration. If such improvements do not occur then the perceived value is greatly reduced.

In addition, modern configurations of solar cooling systems are oriented primarily at commercial level, rather than at household level. This created a question on the actual relevance and functionality of these policies for the average consumer. Gas geothermal systems are still costly and have questionable efficiency ratings and, as a result, many homeowners consider them less economical than traditional air conditioning systems.

The issues related to system design add the layer of challenge to the topic of finance. The application of many technological components entails the need for professional installation and maintenance skills which may not be readily available locally in the contractors' service providers. This could lead to higher costs when it comes to hiring qualified personnel for initial installation or in case of a problem solving.

Apart from financial barriers that are directly related to the deployment of solar technologies, there are other economic barriers of solar technology adoption. The markets for renewable energy solutions remain emergent; hence, policies that promote investment through subsidies or rebates are vital, though frequently poorly designed or applied unevenly across different markets. The absence of such policies reduces the confidence of potential consumers whenever they are planning to invest in photovoltaic driven cooling solutions.

Another crucial economic concern relates to the costs incurred over the lifetime of decision making between photovoltaic-fed systems and other conventional options. Some works show that there are potential long-term financial benefits, such as saving on electricity to meet cooling demands through direct use of solar energy; some buyers tend to consider only the price tag at the time of making a purchase instead of investment returns in the future.

Last but not the least, the level of awareness among the public concerning photovoltaic- driven cooling solutions is still low. The problem is that a vast number of people possess limited knowledge on the range of possibilities and advantages of utilizing such technologies, as well as fear of losing money, which hinders them from investing in these technologies. It is possible that educational programmes aimed at enhancing the understanding of the benefits and future cost implications could go a long way in demystifying the disbelief associated with such innovative strategies [8], [13] and [30].

## 6. Future Directions

### *6.1. Emerging Technologies and Trends*

The advances of photovoltaic cooling systems' technologies are changing the conventional energy-efficient and sustainable approaches. One emerging type concerns new classes of materials and configurations of solar collectors, especially the efficient dual-function photovoltaic-thermal (PVT) collectors that simultaneously produce electric power and heating or cooling. This integration improves energy use by integrating heat collection with power production.

Newer developments revolve around the selection of new working fluids to enhance the COP of the absorption refrigeration systems. Research shows that alternative fluids can raise the thermal performance under certain conditions and mitigate drawback of conventional refrigerants.

Nevertheless, the applications of phase change materials (PCMs) for thermal management in cooling systems are emerging as a new interest. PCMs store and release thermal energy in the form of latent heat during phase transitions and are able to work in conjunction with PV systems to regulate the internal temperature prevailing as the external environment changes.

Micro fluid cooling technologies are also being adopted, where micro channel structures in the solar panel reduce heat dissipation. These innovations assist solar cells in avoiding excess temperature, thus decreasing thermal depredation, enhancing life expectancy, and increasing power production.

Another new concept is artificial intelligence, as well as machine learning in this field. Based on the weather data and system performance, these technologies adjust working parameters in real-time, thus, promoting the better control of energy and solar energy production.

More often, we have bifacial solar panels, which are able to collect light from the both sides, which increases the amount of collected energy and decreases thermal load. Additional features such as dynamic shading and tracking systems enhance the performance of the panels in the course of the day.

As researchers continue to search for new solutions to thermal problems in systems driven by PV, these technologies will have better efficiency, cost of the solution, and realistic implementation. Technologically inclined manufacturing techniques such as roll-to-roll printing for flexible PV modules are noteworthy steps toward achieving the PV cost reduction and potential application in various sectors [4], [25], [36], [13], [43] and [27].

*6.2. Potential for Policy Changes and Support*

It has been found that the implementation of photovoltaic-based cooling systems can be greatly boosted with policy changes and support. With increasing population and thus demand for electricity, these technologies are well situated to be enforced by current policymakers in order to provide research and innovation for solar cooling. This could include subsidies of private firms and universities to research on how to enhance the efficiency of photovoltaic conversion.

Approving and implementing photovoltaic cooling solutions into the building codes of the country will help achieve a switch towards green energy. For example, management could make renewable electricity generation mandatory in new construction to popularize solar cooling technology as a necessity rather than a luxury as the world moves towards green status, supporting the environment as well as the green economy market.

It is also important to note that P–P collaborations provide mechanisms for fusing resources to address issues, including high cost of implementation and system complications. Large scale projects where photovoltaic cooling has been implemented and proved successful may be set up by the government to encourage others to do the same.

It is also important to launch educational programs with the aim to spread information about possibilities and specifications of solar cooling systems. Capacity building of engineers, architects and builders will enable a skilled human capital who would be in a position to implement these solutions.

This is so because the initial investment outlay is a major determinant of acceptance and hence economic factors compel the need for policy changes. Possible financial plans with a long-term saving perspective motivating stakeholders to embrace photovoltaic cooling include cutting down energy use. It may also offer financing sources, performance bonds in order to manage the investment risks.

On the international level, some other opportunities for enhancement are linked to the correlation between the identified policies and global sustainability goals. Those nations pursuing a goal of lower carbon emissions can incorporate renewable sources such as photovoltaics into their strategies and promote the exchange of knowledge and technologies between nations. It is important that issues concerning the irregularity of supply of the solar energy especially during the nighttime is addressed; this has necessitated the development of other related technologies such as batteries and Solar/Wind hybrid systems. By making new appropriate changes in the policies, it is possible to foster the shift in energy conservation practices, also advance, and develop the photovoltaic cooling systems [14], [8] and [40].

## 7. Environmental Impact of PV-Driven Cooling Systems

*7.1. Reduction in Carbon Footprint*

Photovoltaic air conditioning systems provide the specific potential for cutting off greenhouse gas emissions usually linked to routine cooling techniques. One of the strengths of these systems is that they can work off the grid using power from solar energy as a form of renewable energy. This independence causes a considerable reduction in emissions of greenhouse gases especially carbon di-oxide which is known to have a lot of impact on world warming. Some of the studies indicated that solar powered cooling systems could realize significant TEWI reduction in comparison to the conventional vapor compression cooling units.

For example, research shows that an off-grid photovoltaic (PV) air conditioning system consumes no grid electricity and boasts a very low TEWI of only 0.648%, placing it as an environmentally friendly product. Traditional air conditioning uses fossil fuel or electricity produced from burning of these fuels, hence has much larger carbon footprint.

Another important area of application is the improvement of sustainability of cooling solutions through the integration of solar thermal technologies. Using solar adsorption or absorption chillers these system also reduce the dependence on electricity from fossil sources. Published works indicate that some adiabatic cooling systems can be capable of reducing coh2 emissions of as much as 90.7% less than the electrically powered conventional cooling systems.

Furthermore, the practical application of photovoltaic-driven cooling technologies enhances energy usage since the cooling processes are energy consuming. For instance, annual simulation shows that solar driven absorption and adsorption cooling units are having comparatively lower primary energy consumption than the electrically driven ones. One research that contrasted water-cooled vapor compression and solar-driven vapor absorption systems concluded that implementing the latter could reduce more than 1.65 million kWh a year’s worth of primary energy.

Furthermore, as climate change intensifies resulting to high temperatures in urban environments and in parallel with high demand for internal building temperature comfort, the use of photovoltaic-driven solutions not only meets energy demands, but also reduces urban heat island effect – a factor that contributes to climate change.

These sustainable technologies have the ability to be implemented globally and in every climate and region, and by doing so the negative impact of conventional cooling techniques on the environment and the promotion of renewable energy is vast. These photovoltaic powered systems remain economically feasible due to technological developments and declining installation costs especially to the extents that they can be used in homes and businesses.

Therefore, photovoltaic-driven cooling systems are another innovative way of realizing a quantum leap in the reduction of carbon emission associated with conventional air conditioning apparatus and at the same time supports global fight against climate change, [12], [20], [3] and [2].

**Table 2**: 3E results of VCC and ACS system, [12]

| Sr. No. | Parameter | VCC System | ACS System |
|---|---|---|---|
| 1 | Annual primary energy consumption (kWh) | $2.23 \times 10^6$ | $5.74 \times 10^5$ |
| 2 | Annualized capital investment cost (Rs.) | $1.07 \times 10^7$ | $3.31 \times 10^7$ |
| 3 | Monthly running cost (Rs.) | 1,612,186 | 393,269 |
| 4 | Annual $CO_2$ emissions (tons) | 346.78 | 108.58 |

*7.2 Contributions to Sustainable Development Goals*

Energy in cooling systems from photovoltaic means aid in the degrees of sustainable development since they respond to environmental, economic and social needs. One is their ability to mitigate greenhouse gas emissions and the study shows that solar cooling can decrease CO2 emissions by 99% compared to conventional methods. It is important for the fight against climate change and assists in moving to a low-carbon economy.

In addition, it is observed that the photovoltaic cooling technologies improve energy conversion efficiency, which results in large primary energy saving. Research shows that the application of solar-driven absorption cooling systems can eliminate millions of kilowatt-hours yearly and save the energy that can be circulated in local markets.

These systems also encourage the growth of the economy through employment opportunities, as well as enhanced establishment of industries. The setup and management of photovoltaic technologies call for human resource input hence acting as sources of employment. For instance, they used the penetration of PV electricity to cool storage in the developing countries to revolutionize the fishing sector to enable preservation of fish without the use of costly power sources.

In equity aspect, solar cooling solutions ensure availability of cooling solutions to the people in the remote or disadvantaged areas. In agriculture, these systems contribute to decrease the post-harvest loss to increase food security and meet health related goals associated with food safety.

In addition, the sun photovoltaic cooling technologies benefit from wide adaptability making those suitable for providing sustainable solutions that address the needs of different climates in residential, commercial sectors, and cold storage among others. It also becomes realistic where there is enhanced technology, and the costs of production are put down.

Finally, photovoltaic-driven cooling systems illustrate various ways that renewable energy technologies enable the achievement of multiple United Nations Sustainable Development Goals, such as clean energy, climate action, sustainable cities, responsible consumption, and life below water, which are valuable to society and the environment, [42], [20], [12], [9], [7], [16], and [34].

## 8. Economic Impact of PV-Driven Cooling Systems

### *8.1. Cost-Benefit Analysis*

The assessment of photovoltaic-enabled cooling systems shows that these technologies are more efficient for cooling in the end from both financial and environmental perspectives. Although the installation cost of PV-based systems is compared to conventional technologies higher, their Lifecycle cost are significantly lower. Studies done indicate that solar thermal systems will have higher energy consumption rates as well as the associated cost but photovoltaic systems can save much more due to reduced reliance on grid electricity.

Furthermore, the cost per kilowatt of cooling is highly favorable for PV solutions when compared to the initial costs of the solution. This study established that an off-grid PV-powered air conditioning unit was 54.88% cheaper per kW than traditional electricity, which ranged from 295%. This massive variation primarily arises from the exclusion of fuel costs and the relatively low level of maintenance necessary for photovoltaic technology.

When the operational life, often expected to be around 20 years, is taken into consideration, it is clear that PV solutions therefore have a more appealing discounted payback period than both thermal choices and standard air conditioning equipment. Thus, apart from direct costs, such economic estimates take into consideration the life cycle costs, including maintenance and replacement.

These environmental impacts further add to the attractiveness of the photovoltaic-driven cooling solutions that emit significantly lower levels of greenhouse gases than the thermal based solutions. Studies show that solar electric cooling has overall TETW value much lower than those of conventional ways do. This corresponds well with other sustainability objectives in efforts to minimise the use of fossil energies and overall carbon footprint.

Another important consideration of this economic assessment is whether PV-driven cooling performs satisfactorily under different climatic conditions and whether the resulting financial implications may vary significantly in per-optimal solar irradiant locations. Where energy requirement best matches with solar energy supply that is hot dry climate these systems turn out the best parameters of performance and thus much higher rate of return on investment.

To conclude, while many potential users may be put off by the initial costs associated with abandoning traditional cooling methods, constant technological progress is today reducing these start-up costs even as it optimizes systems' overall efficacy and effectiveness in the longer-term. This development holds the appealing prospect for both residential and commercial sectors to adopt photovoltaic-driven cooling technologies, [15], [22], [2], [11] and [18].

### *8.2. Long-term Financial Viability*

The viability of cooling systems based on photovoltaic technology for their funding in a long term depends on such factors as the amount of investment, and the savings made throughout the operation period, as well as the outlook for energy prices in future. Despite the high initial costs, it requires high net profit for installation, innovation in technology and decreasing prices for photovoltaic factors make these systems far more appealing. For example, where projections have been made up to 2030, SECC will demonstrate lower first costs than conventional systems due to the enhanced efficiency and reduced cost of photovoltaic components.

The cost advantages of photovoltaic cooling systems are greatest in regard to the significantly lower operational costs. Since these systems use free solar energy for cooling, they can greatly result in lower electricity expenses. The payback period becomes an important measure of financial feasibility; this period is anywhere between five and fourteen years depending with factors including geographical location and system design. Nevertheless, if the operational costs are reduced, which will take time to achieve then the long-term investment more appealing as this timeline can be shortened.

Moreover there are also many countries giving incentives for renewable energy source including solar powered cooling solutions so enhancing the viability of solar cooling. Such incentives may include tax credits, grants, or feed in tariffs all of which play part in reducing initial costs and improving cash flows from these programmes.

Market dynamics are also potential for long-term sustainability. When the prices of the fossil fuel go high and the government regulations on emission of greenhouse gases tighten the use of renewable sources like the photovoltaics will prove to be cheaper. As well as helping to offset risks associated with fluctuating energy costs, it is also well in line with more overarching sustainability strategies.

However, their economic performance can be even improved if these systems are linked to smart grid or energy storage technologies. By either managing their energy consumption during high demand or by permitting consumers to send the stored energy back into the grid when price goes up, investors stand to gain the most.

Nonetheless, current obstacles that need to be overcome so that industry may take up photovoltaic-driven cooling systems for life cycle cost savings and environmental benefits in the long term include technological factors and appropriate policy strategies, [15], [27], [22], [18], and [3].

## 9. Conclusion and Recommendations

### *9.1. Summary of Findings*

Solar photovoltaic cooling technology can be deemed as one of the most important innovations of green technology as they are powered by photovoltaic to deliver cooling solutions. The findings of this research point to the vast potential of these systems to decrease dependence on conventional fossil resources and minimize negative effects on the environment, particularly in the production of greenhouse gases. Major discoveries suggest that photoelectric system can closely or even surpass other cooling systems by greatly reducing the electricity usage and overall cost of running the facilities. For instance, research indicates that appropriately integrated solar cooling technologies can save as much as 80% extra energy than normal air conditioning systems.

Application of photovoltaic-driven systems is made efficient by modern innovations like micro fluidic cooling system and phase change materials. Such dynamic simulations have shown that the designs that have been optimized enable the system to have improved thermal efficiency and lesser electrical requirements during different seasons. This flexibility not only increases performance but also on the same measure reduces overall energy cost of conditioning the air.

Photovoltaic-driven cooling best practices are illustrated by a number of examples that are based on real-life projects and highlight both the usage of photovoltaic-driven cooling in residential buildings and in commercial facilities. These examples serve to illustrate the practical advantages of incorporating solar technology into cooling systems – some of them are expressed in the decrease of primary energy consumption. Moreover, the LCA analysis conducted shows that solar integrated cooling solutions have a lower climate change impact than cooling systems relying on electricity from the grid during their use phase.

Reasons for considering these technologies reasonable are also supported by economic analyses with rather attractive cost-benefit ratios. This study shows that the initial costs of installing the system are recovered from the savings in electricity bills and other maintenance expenses in the end. Furthermore, with the progress of the technology and its diffusion it is expected that governmental subsidies for financial will boost the market even more.

However, some issues still linger as to how performance under various conditions of application can be optimized and how the use of the system can be made cheaper than traditional systems. To resolve these problems further research is necessary, focusing on the integration of systems and examining new forms of integration of thermal solar components and photovoltaic parts. Such innovations could enhance the reliability of the system while at the same time extending the potential of others for heating and cooling at the same time.

Therefore, photovoltaic-driven cooling systems remain highly relevant and are promoted as an essential element of sustainable development initiatives designed to achieve lower carbon emissions in line with the expanding demand for efficient climate control in different industries. Subsequent research must be conducted to improve the understanding of the system dynamics and identify further opportunities to optimise the utilities for users across the world, [4], [35], [8], [13], [23] and [32].

*9.2. Research Gaps and Future Work*

The study of photovoltaic-based cooling systems bring further opportunities for future study especially concerning the advancement of energy efficient and sustainable cooling technologies. There is a dearth of exhaustive simulation-based studies undertaken systematically to analyze the performance of PV driven refrigeration cycles. While several studies have focused on different aspects of these systems, a systematic way of modeling the system could improve the comprehensiveness of the approaches toward evaluating the operations and effectiveness of the systems.

Future research should also be devoted to combined cooling systems with photovoltaic equipment used in conjunction with other types of renewable energy or storage units. These hybrid models show that COP is generally enhanced, and it appears that by focusing more on hybrid configurations rather than exclusively on PV driven cycles, could bring great gains.

Another research opportunity that has been identified relates to the enhancement of design parameters particularly the angles of tilt and position in relation to the sun. Since these factors may be modified to greatly affect system performance and energy harvesting, more focused studies on, their effects should be conducted across various climate zones.

Thirdly, the applicability of other materials as well as nanotechnology in cooling technologies is also a promising research area. With the help of thermal characteristics of these innovations, it is possible to create effective, low energy consumption cooling systems that will enhance the functionality of the use.

Furthermore, the strong focus on the incorporation of smart technologies into PV-driven systems should be underlined. Applying the adaptive control systems with elements of artificial intelligence and machine learning can help to increase the effectiveness of the systems, and to tune them with the help of additional parameters that reflect the current conditions and needs of the system users.

In addition, they conclude that there are few studies that done to investigate the overall performance of PV driven cooling system with the conventional air conditioning technologies in different operating conditions especially in hot and dry climate zone. These comparative assessments are crucial for both the economic rationality of the various system types as well as their environmental consequences.

Due to the existing deficiencies in the utilization of TES technologies in photovoltaic applications, additional research on the enhancement of phase change materials (PCM) is necessary. Moreover, the ideas could be expanded by incorporating cost-benefit assessments that concentrate solely on the use of PCM in the development of advanced products.

Last but not the least, although further improvements in the concentrating photovoltaic (CPV) technology and its integration with cooling cycles seem to be promising based on initial results, they are by and large uncharted. Additional investigation of this field may uncover revolutionary approaches to creating more productivity in existing energy resources as well as decreasing the emissions of greenhouse gases.

When closing these gaps through specifically oriented research efforts, stakeholders will not only contribute to enhancing technological development but will also contribute significantly to attaining sustainable global standards of energy utilization and combating climate change, [4, 25, 28, 26, 2, 23 & 32].

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