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Decentralized Solar Cooling Systems for Urban and Rural Applications: A Comparative Analysis

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ABSTRACT

This paper looks at distributed solar cooling systems and assesses the viability and the advantages of such systems under both the urban and rural contexts. This paper provides a detailed comparison of these systems, with special emphasis on energy performance, environmentally friendly features, and variation in climatic conditions. Specifically, the authors focused on the follow issues associated with cooling solutions in the framework of global warming and increasing urbanization: energy intensity, environmental footprint, and the dependency on fossil fuels. Most conventional cooling systems, including air conditioning, rely mainly on fossil energy and hence are a major source of greenhouse emissions. Decentralized solar cooling systems seem to offer a way by acting as eco-friendly cooling systems that are independent of the conventional energy supply. These systems capture and convert solar energy into usable cooling power for application in places with intermittent or constant high heat such as in urban as well as rural areas. The benefits are; less transmission loss, improved energy reliability, and less CO2 emission as compared to centralized system. Further, distributed structures enhance the availability of cooling in areas which are served by a weak grid power supply, especially in rural areas. The paper also explores various technologies that include photovoltaic panels and thermal collectors which make such systems functional in different circumstances. Nevertheless, several problems limit the application of the decentralized solar cooling systems. The problems associated with system complexity, maintenance, high costs of initial establishment, and absence of favorable policies remain critical for wider adoption. The last section of the paper briefly addresses the prospects of these systems, suggesting that future developments, supportive economic and policy frameworks will be conducive to the scaling up of such systems.

1. Introduction

With increasing temperatures and trend of urbanization, global cooling demand generates challenges of energy consumption and sustainability. Most of conventional air conditioning systems utilize fossil fuels that are environmentally unfriendly and stress the importance of using other strategies. Decentralized solar cooling systems appear as the most efficient solar cooling solution that uses sunlight to satisfy cooling needs and decrease reliance on traditional energy resources.

These systems harness solar energy and make it available for a variety of cooling services in various terrains, be it in populous or in distant regions. In this way, they increase efficiency in energy use and reduce energy losses that are common in centralized systems of cooling. This closeness to demand enhances energy security and reliability as well as

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reducing the carbon impact associated with the conventional cooling technologies.

Decentralized solar cooling relies on equipment such as photovoltaic (PV) panels, thermal collectors that can adapt to different conditions and requirements. Their integration makes sense in relation to the internationally set objectives of sustainable development and the rationalization of the use of fossil fuels. In areas where the energy use is high such as in the urban region, these systems reduce the load on the electrical systems while improving on climate control. In rural places where stable electricity is hard, to come by they enhance quality of life without adding to pollution.

Advancements in technology currently in the market are improving the effectiveness and cost-optimization of solar cooling systems. Future innovations may improve the efficiency of the system and thus extend the use in other climatic conditions. The change is crucial for the development of the economic sector, for the encouragement of responsible behaviors among people.

But there are still issues with decentralized solar cooling system implementation which need to be addressed. Challenges emanating from technical aspects include implementation difficulties, cost of maintenance, and initial costs. In addition, the economic factors, which include, market readiness and supportive policies have been highlighted throughout this work as influencing the acceptance of these technologies. The document will look at samples of use in urban and rural areas where the ideas have been applied to offer the benefits, and the main issues that planners and developers encounter in adopting these solutions, [21], [12], [8], [1] and [7].

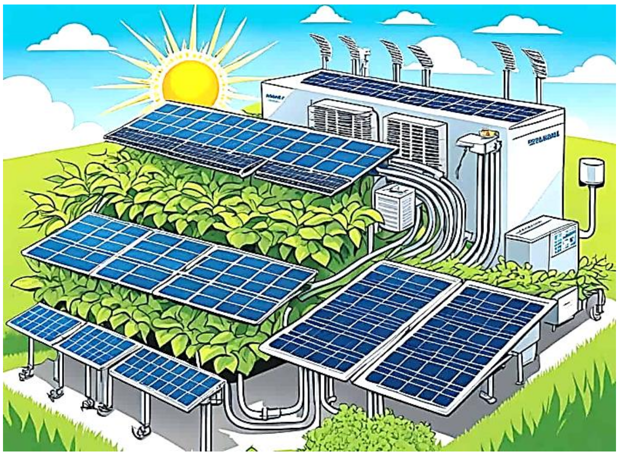

Figure 1. Growth in the Solar Cooling Market, [12]

2. Overview of Decentralized Solar Cooling Systems

2.1 Definition and Principles

Decentralized solar cooling systems uses solar energy to offer cooling solutions in the both the urban and / or rural setting and thus presents a more refreshing approach than the conventional air conditioning that depends on grid electricity. These sophisticated systems operate with the aid of photovoltaic (PV) panels or solar thermal collectors to transform solar power into useful electricity that operates several cooling equipment. With the help of solar energy, they solve the problems like high consumption of electricity and increased emission of greenhouse gasses characteristic for traditional cooling systems.

The major decentralized solar cooling technologies include the solar absorption chiller, the solar adsorption chiller, and the solar evaporative cooler. Absorption chillers depend on a heat source for operation of a refrigerant cycle and make use of substances such as lithium bromide and water. Unlike adsorption chillers use solid adsorbent materials that selectively, selectively condense, and evaporate refrigerant vapor under low temperature conditions and high solar energy. There is a simple natural process that evaporative coolers use: that is the process of making water evaporate, which is highly effective in hot and humid climates.

Some of the main parts of such systems include solar collection surfaces that captures sun’s radiation, thermal or electrical energy storage systems, and advanced and energy conserving cooling equipment. The efficiency of these systems depends on factors of the surrounding environment including the intensity of sunlight, relative humidity, and temperature. Advanced technology has enabled the development of improved designs that raise the COP for several applications.

Decentralized solar cooling is a complete solution of satisfying cooling needs at localized level and sustainable. These systems produce energy near where it is required – also known as distributed generation, hence reducing transmission losses associated with centralised power generation. They also provide reliability where grid electricity is spell or patchy or is not available at all.

Apart from its environmental impacts, decentralized solar cooling systems have economic impacts by reducing reliance on fossil fuels and operational costs on electricity consumption. This makes them especially good for the companies that are striving to cut costs and the owners who want to promote the principles of eco-friendliness.

These decentralized solar based cooling technologies are ready for uptake in different sectors of the world from agriculture to cool storage, from commercial to residential buildings to improve living standards without increasing the global warming impacts.

The major weaknesses of decentralized solar cooling systems are largely associated with the initial costs of installation and subsequent maintenance that may be a limiting factor towards the widespread use of the systems. However, in practice, factors such as governmental subsidies or innovations generated by the market could greatly enhance their adoption into the common practices, [8 and 5], [12 and 7].

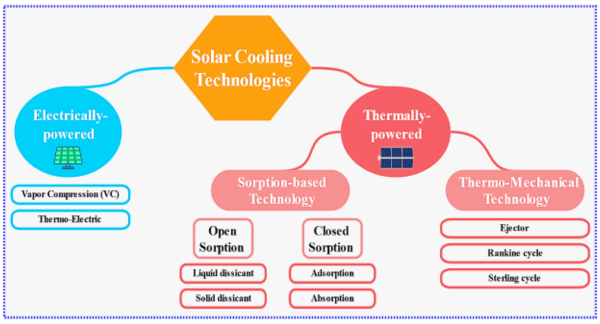

Figure 2. Main solar cooling technologies, [18]

2.2 Types of Decentralized Solar Cooling Systems

Decentralized solar cooling systems can be generally classified into two main categories: solar assisted cooling systems and solar powered cooling systems. The first type harness the sun through collectors and turns it to thermal energy that is then used to operate the different cooling systems. This includes absorption chillers, desiccant cooling systems, and the Adsorption chillers. An absorption chiller employs heat energy in the absorption of the refrigerants while an adsorption chiller uses material structures to absorb and release moisture hence delivering the cooling mechanism. Desiccant systems use materials with high ability to absorb moisture from the air hence reducing humidity to create cooling effect.

On the other hand, solar electric cooling systems use photovoltaic (PV) systems which produce electricity to operate a traditional compressor that uses the vapor refrigeration cycle. These PV panels convert direct sunlight into electric power that is used in normal electric chillers or thermoelectric convertors. This method is particularly suitable for application in small-scale installations where the electrical installation can comfortably incorporate solar technology.

In the large categories of these applications, several distinct technologies have been developed. Solar absorption technology is recognized as one of the solar thermal cooling technologies and its applications are characterized by single and multi-effect systems that increase the absorption of heat by passing it through several stages. Adsorption technology is similar to absorption technology, but it normally takes place at lower temperature than the absorption technology but possesses some merits in conditions where high efficiency at lesser capability is required.

In addition, to boost performance and flexibility, integrating different technologies is also more common and is called hybrid solutions. For example, hybrid systems may consist of both the PV panels and thermal collectors where energy is used optimally in the given climate or at different times of the day.

Another major development made in decentralised solar cooling technologies is the application of solar driven ejector refrigeration cycles. They use principles similar to jet propulsion powered by thermal energy gotten from solar energy to make efficient refrigeration without using conventional compressors.

The last few years have seen quite a number of advancements on the use of machine learning and optimization to enhance performance characteristics of different solar cooling systems. Improvements in the materials used in the desiccants or sorbents also helps raise system efficacy and lower maintenance and running costs.

Nonetheless, the decision on which of these diverse forms of decentralized solar cooling systems to employ depends on factors that include size (residential versus commercial/industrial), location (urban/peri-urban/rural), climate (temperature fluctuations), space (roof-mounted versus ground), and monetary including cost/benefit ratio of the system, [3], [5], [7], and [18].

2.3 Technology Components

Small-scale solar cooling systems encompass several technological subsystems that enable the utilization of solar energy for cooling processes. At the core of these systems is solar thermal collector that is used to harvest solar thermal energy. Among the more popular types, there are flat plate collectors and evacuated tube collectors. Flat plate collectors use a black surface on the absorber plate for collecting sunlight while the evacuated tube collectors are made of tubes made of glass in order reduce heat loss and hence improve on their efficiency even under low temperatures. Further, concentrating solar power systems can also be integrated into decentralized cooling systems; CSP systems utilize mirrors or lenses to focus the sun light and achieve high temperature for heating application or directly to thermally driven chillers.

In addition to solar thermal collectors, energy storage systems are one of the most essential components to ensure continuous, reliable cooling during the time of no sun. The techniques of thermal storage are mainly sensible heat storage and latent heat storage. Sensible heat storage is a direct method of storing thermal energy by heating water or other heat transfer fluid for later use, whereas latent heat storage is based upon the use of phase change materials that absorbs or release energy during its phase change from solid to liquid or vice versa. They help manage demand side since they allow consumers to use most of the energy during off peak hours.

The other important part is the cooling technology that has a possibility to use different technologies like vapor compression and absorption chilling circles. The vapor compression systems work similarly to conventional air conditioning systems but when in connection with the PV system, they can be directly operated using electricity from PV panels. On the other hand, there are absorption chillers which use heat as a driving energy source and are therefore most appropriate for decentralized systems which use CSP or solar thermal energy.

Thermal sorption chillers are another innovative solution in the decentralized solar cooling systems described. These appliances use substances that are employed in adsorption by solid materials or absorption by liquids to cool the absorbed refrigerants when heated by solar energy. Its benefits include lower electric energy consumption than conventional vapor compression systems and the capacity to utilize low-grade heat.

Beyond these key elements, control systems are crucial for enhancing performance of distributed solar cooling processes. Sophisticated control techniques permit optimal control by periodically checking temperature and loading conditions and adapting the corresponding outputs in order to control comfort requirements.

Further, backup systems make the decentralized installations more robust against variability in weather, specifically in terms of the availability of sunlight. Electric vapor compression chillers are typically employed for these configurations as auxiliary systems so that chill water can be provided even when solar input is insufficient.

Altogether, technology features under consideration lead to highly efficient decentralized solar cooling solutions, which can contribute to reduction of greenhouse emissions and provide cooling services that can be adapted to urban and rural areas, [24], [11], [15], [3], [1], [7] and [4].

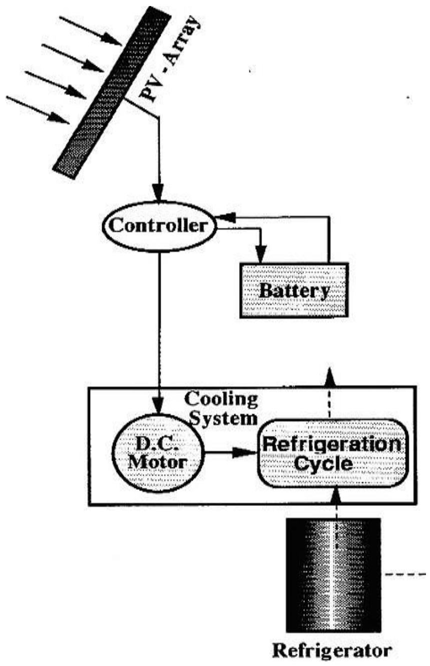

Figure 3. A configuration of PV solar-powered vapor compression systems, [7]

3. Urban Applications of Decentralized Solar Cooling

3.1 Case Studies in Urban Settings

Decentralized solar cooling systems are more appropriate in the modern urban setting in view of the issue of urban heat. A good example of this is the Charlestown Square Solar Thermal Cooling System in Australia that has been in operation with a 230 kWr absorption cooling system since 2011. It employs a solar array with 12 PolyTrough 1200 collectors to produce pressurized hot water for a BROAD double-effect absorption chiller for producing chilled water to a shopping mall. This project underscore the need for proper design of the solar collectors and proper control of the system in order to get the best out of the solar energy.

Among others, there is a project of a football stadium in Qatar where the company will implement sustainable initiatives during the World Cup 2022 bid. This facility has an integrated 1 MW absorption chiller powered by a CLFR Solar Collector Field covering an area of 1,400 m². Besides, it also guarantees comfort and prioritizes carbon neutrality as one of the priorities of a contemporary city.

The adopted solar thermal technology with an integrated cold storage room is manifested in the urban agriculture context in Germany through the AgroKuhl project. Installed at Kramer GmbH in Umkirch, this system uses a large solar collector array to cool horticultural commodities optimally under regional climate. The COP of the decentralized solar cooling project is 1.2 and the first outcomes show great results, therefore, it influences the idea of improving food security and sustainability.

Cities across the world are learning the advantages of de-centralized cooling systems that will reduce on the effects of extremely high temperatures due to climate change andurbanization. Various measures like making cool islands in some cities like Paris and Ahmedabad, and using reflective materials on rooftops etc.

In addition, the passive cooling of solar photovoltaic (PV) panels in the densely-populated area is an area of increasing concern. One of the current research studies that has been carried out on advanced cooling techniques involving the utilization of re-usable gel packs has indicated high prospects in the enhancement of the PV efficiency besides minimizing the use of conventional and energy intensive A/C technologies.

In total, decentralized solar cooling systems contain viable solutions and prospects for improving energy efficiency and sustainability within cities, [17], [3], [22], and [3].

3.2 Benefits for Urban Areas

Decentralized solar cooling systems present several benefits for urban settings, solutions to issues such as increased temperature, energy consumption, and environmental problems. One advantage is that they can be used to manage high demand on electrical networks in summer, which would significantly decrease the load on energy sources and improve energy access.

These systems ensure environmental conservation as they use renewable forms of energy unlike other cooling methods that use fossil energy and hence degrade air quality and increase greenhouse gas emissions. For healthier living condition, it becomes important to adopt cleaner technologies because cities are feeling the impacts of climate change.

On the economic utility side, decentralized solar cooling saves residents and businesses significant expense by reducing demand for costly grid electricity in areas with high tariffs or unreliable supplies. By having this consistent access to cooling, cost become high and financial stability is not an issue.

In addition, municipalities benefit financially from these technologies in one way or the other. Lower energy usage also means less energy cost for municipalities, and less stress on the energy resources, which frees up budget for other important areas like education or police work. Further, smart grid systems' roll out introduces localized employment chances regarding installation and servicing of the systems.

Most cities experience higher temperatures than their rural counterparts this is known as the urban heat island effect or UHI. Decentralized solar cooling technologies minimize the intracity heat island effect because they cool specific areas and decrease the absorption of heat in cities.

It also has a positive positive impact on social justice by providing cooling to citizen's especially those that cannot afford the modern air conditioning systems. Thus, cities may meet the goal of providing renewable-powered cooling to vulnerable population groups who are in danger of heat exposure and thereby enhance the health of these populations.

The inclusion of these technologies to urban planning serves the purpose of smart city development. With regard to urban sustainability that strives to focus on energy effectiveness and reliability of the framework, decentralized solar cooling contributes to energy saving and improving the quality of life. Finally, decentralization enhances relevance of the solutions to the needs of the communities without overdependence on central facilities, developing new ideas to make cooler environments for all the residents of cities, [14], [22], [22], [8], [26] and [22].

4. Rural Applications of Decentralized Solar Cooling

4.1 Case Studies in Rural Settings

Decentralized solar cooling solutions are the ones revolutionizing numerous rural regions when it comes to cold storage in agriculture. A solar-hybrid adsorption cooling system has been developed in India for extending produce shelf life using solar energy and biomass waste heat, critical in areas with unstable electricity supply. This approach is for the purpose to tackle post-harvest losses due to non-availability of proper cold chain where 30% losses are reported.

In Pakistan, farmers are using solar technology for cold storage to overcome post-harvest losses that are quite alarming. These systems can work well in the country since the average solar irradiance varies from 5 to 7 kWh/(m² d). Solar energy enables farmers to cut down the dependence on conventional electricity networks and derive varying energy saving from 40%-50%. There is also a new generation cold storage with cooling pads as a standby during harsh weather to maintain the right temperature for the products.

Africa has also stepped it up with such things as SelfChill that is reputed as one of the best solar cooling systems. This off-grid system intended at the smallholder farmer with no control over electricity, powers coolers for perishable commodities. Such systems are most necessary in regions where approximately 25 to 40 percent of harvested crops are likely to rot because of ineffective cooling.

The overall prospects for solar-powered distributed cooling around the globe is huge, especially, because Africa, for example, could produce hundreds of petawatt hours per year through solar sources. There is a crucial opportunity to reduce food waste and increase farmers' revenue by investing in distributed cold storage close to production hubs.

These systems have been enhanced through technological development, for instance the development of VFD and compressors to enhance on energy conservation; or the design of modularity of these systems based on the requirements of the region. Nevertheless, there are issues that hinder the use of these technologies such as viability in areas of economic returns and knowledge among the smallholder farmers most of who lack the capital to fully fund the implementation of these technologies. To solve these problems, it is essential to develop specific strategies and stimulus programs, such as subsidies or financial assistance that aimed at reducing the initial investments and deployments of the decentralized solar-powered cold storage facilities, [20], [25], [16] and [10].

4.2 Benefits for Rural Areas

Decentralized solar cooling systems have many benefits for rural areas, especially for increasing production in agriculture and food security. These technologies help in minimizing post-harvest losses that is a common problem in areas where farmers get limited access to cool temperatures. For instance, smallholder farmers estimate post-harvest losses ranging between 15 to 25 percent due to a lack of access to cold storage. Through increasing efficiency in cooling perishable produce like fruits and vegetables, advanced solar cooling technologies enhance preservation of the produce from the farm to the consumers.

In rural areas, these decentralized solar cooling systems do solve the issue of lack or complete absence of electrical grid. Large areas of the countryside have unstable sources of electricity, which excludes them from the use of standard methods of refrigeration. Solar cooling solutions do not require the operation of the grid as the primary source of energy for their functioning. This is even more beneficial to areas that have a lot of sun but little electricity infrastructure. These systems work with the help of local renewable energy sources that help in minimizing the use of fossil energy and build a sustainable agriculture system.

Furthermore, the use of such systems can open economic prospects for the development of rural areas. When farmers are able to store their produce well to reduce losses through spoilage, they can be able to supply the markets more as they possibly try to negotiate better prices for fresh produce. This not only increases people's income but also revives the regional economy through building up the agricultural value supply chains. Furthermore, decentralised solar cooling facilities mean employment opportunities concerning system installation, maintenance and operation within these communities.

The incorporation of ICT in the traditional farming processes of the rural agriculture also creates innovation and enhanced information transfer between farmers and co-operatives. Measures used with coolers employing solar energy generally entail training the local operators and maintenance personnel. This capacity building aspect ensures that community will gain the requisite capacity in order to effectively run the systems in the future.

Moreover, decentralized solar cooling plays a very important role in improving the climate change adaptation since its implementation is characterized by low or zero emissions of greenhouse gases compared to conventional cooling technologies based on hazardous refrigerants or fossil fuel. As climate change affects agriculture including influencing crop yields through heat, solar cooling is a sustainable solution that fits the conservation agenda.

Another benefit is that SAMS is easily scalable; the small modular systems proposed can be developed to address certain requirements in a range of farming operations while necessitating minimal large-scale facilities investment. This flexibility gives the opportunity to base the solutions found on the communities the members of which are engaged in farming or on particular crops in that farming.

Data from pilot programmes in different parts of the globe, including Ethiopia, shows that cooling containers run on solar power have been incorporated into co-op structures in which various farmers pool resources and decision-making and every individual farmer bears little risks since the costs are shared by many people.

In conclusion therefore, decentralized solar cooling systems offers a number of opportunities as listed below: The decentralized solar cooling system is specifically suited for rural areas because it solves energy accessibility challenges for agricultural productivity and food preservation while at the same time promoting viability within the said communities, [6], [16].

5. Comparative Analysis: Urban vs. Rural Applications

5.1 Effectiveness in Different Environments

As stated earlier, the performance of decentralized solar cooling systems differs with the environment in which they are implemented. Such systems can help to decrease reliance on conventional energy sources in populated and energy-intensive urban areas as well as to minimize heat island impact and increase energy efficiency. Applications in urban environments include, the photovoltaic thermal (PVT) collector, which offers both heating and cooling and the building integrated photovoltaics (BIPV), which optimizes energy, yields the use of space.

However, rural applications focus on energy independence because most of them lack centralized electricity supply. Here, decentralised solar cooling successfully exploits the Freestanding Solar Resources for Agriculture and Residential purposes. This includes solar-boosted water heaters and desiccant-assisted cooling systems that are well suited in regions with weak power supply networks in the countryside. Some of the cases reveal that rural systems get high operational effectiveness due to the consideration of climate factors and local resources.

That is why the performance of these systems is largely dependent on the local climatic conditions. CO of plants located in areas with consistent mild weather and high level of exposure to sunlight produce higher COP than areas with fluctuating weather. The study reveals that the level of COP varies widely in different systems; for example, the performance of the absorption chillers increases in hot and dry zones compared to the tropical regions.

Energy storage systems add efficiency to these systems by storing heat during the day to use at night and during changes in demand. Thermal storage is used in rural configurations because they are cheap, whereas geometry constraints reduce the choices in urban configurations.

It should also be noted that the economic factors also have a particular impact. Compared to urban projects, rural projects may have lower costs because of the lack of sophisticated equipment and/or adaption of infrastructure, but this comes at the expensive of significantly higher electricity costs that may take a long time to recover through capital improvements. On the other hand, rural installations are characterized by relatively low initial costs and substantial increase in agricultural production rates of returns.

In conclusion, decentralized solar cooling systems are a function of technology advancement, climate and resource availability meaning that future designs ought to consider design variations according to urban and rural settings, [15], [2], [3] and [1].

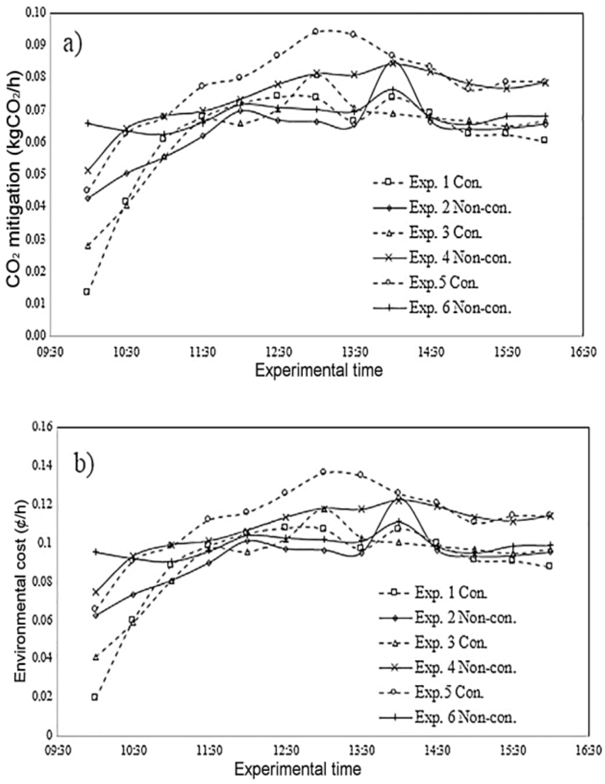

Figure 4. (a) the amount of CO2 mitigation and (b) the environmental cost is a measure of savings achieved by avoiding the production of CO2 concentration, [1]

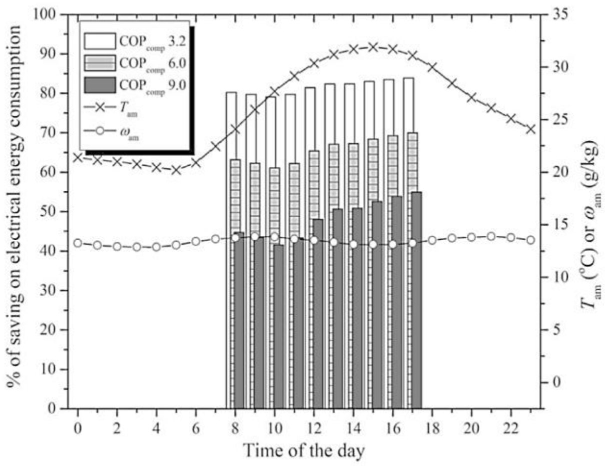

Figure 5. On 18 December, GPVTDC saved % of electrical energy compared with compression cooling, [1]

5.1 Cost-Benefit Comparison

Decentralized solar cooling is therefore likely to involve a rational assessment of initial and future costs. Start-up costs are largely dependent on type of technology, size, and geographical area. It may cost \$500-\$2000 kW of cooling by solar thermal cooling systems, while solar electric power plants may cost \$1000 kWp. While these first costs are higher than those of conventional air conditioning systems, which have a high initial cost but much higher operating costs in the end, solar cooling systems are an attractive option, especially for the future.

These systems harness renewable energy forms, especially solar power, which is easily available in many places and cuts out the need for electricity that is expensive at times. The payback periods of solar cooling technologies depend with the various underlying conditions, with thermal applications having payback periods of between 5-20 years and solar electric systems having average payback periods of between 10-18 years under optimum conditions. High solar radiation zones are associated with higher efficiency and shorter payback periods.

Besides the economic advantages, in terms of energy cost savings, decentralized solar cooling technologies have benefits such as fewer moving parts and greater reliability than conventional units, which usually deteriorate and need to be replaced every eight years. Solar systems that are well designed should have a life expectancy of fifteen to twenty years with little or no maintenance.

In addition, environmental benefits are also accrued since solar cooling solutions do not use detrimental refrigerants to the atmosphere and the environment in their operation to reduce carbon footprint. At a community level, the implementation of these systems can foster the economic development of the area in the sense that it creates employment opportunities within the renewable energy sector; installation, maintenance, manufacturing among others.

Availability of funds plays a role on consumers' ability to invest; therefore, subsidies or incentives are important for increasing perceived value. In summary, decentralized solar cooling systems may be costly initially, but they are likely to generate high returns on investment, environmental returns, and socio-Economic opportunities at individual, household, community, [4], [12], [11], [19], [2] and [13] levels.

6. Challenges and Barriers

6.1 Technical Challenges

Decentralized solar cooling systems have the following technical challenges that make them hard to deploy: The most critical problem of solar energy is the fluctuating supply that hinders cooling efficacy in conditions of cloudy weather or other unfavourable circumstances. This variability can reduce the confidence of users in solar solutions; especially in areas that is characterized with few sunny days.

Another challenge is that the use of solar chillers requires much energy than other solar application systems. Whereas, solar irrigation pumps have low energy requirements, chillers may be up to 250% more demanding in terms of power; these needs have to be addressed through refined storage systems in the hope of adequate power supply during peak times.

Battery backup systems allow clean energy to continue being supplied when there is no sunlight for the system to harness, although they are expensive and inconvenient. The initial cost of batteries can be anything between 30 and 40 percent of the total cost of the system and batteries have a tendency to deteriorate to the extent that they require replacement every three to five years, which remains a source of great financial drain for potential adopters especially in our rural areas where funds are scarce.

Another disadvantage of solar cooling systems is the issue of integration or even installation of the systems in a building. Few people are professionally trained to address these decentralized systems and their users may lack the necessary support to fix these issues or enhance their technologies, which may hinder technology adoption.

However, arrangement and orientation of solar collectors are important in improving efficiency but can be challenging to maintain throughout various regions. Many systems are set at fixed tilt according to local latitude, although tilts may be adjusted for seasons as well can improve efficiency, but are seldom done because of logistical problems.

Sociocultural factors continue to play a role in questioning the need for, and efficacy of, these technologies. A large part of farmers and local communities does not know about the advantages of decentralized solar cooling systems, which makes it necessary to launch awareness campaigns. Information is also important particularly geographical distribution since it determines the practicality of the solar technologies. Pre-implementation environmental surveys should be done, although the process of acquiring such information may be difficult especially in developing countries. Solving these issues involves approaches that improve the technological dependability and respond to the perceived economic concerns that prospective users may have. See references: [10], [9] and [1].

Table 1: Open in new tab Operation of solar-powered cold-storage systems for horticultural products: limitations and prospects, [10]

Operational constraints	**Economic**	**High initial cost**	**A solar powered cold storage system costs more than a conventional cold storage system by 30 to 50%. The high price of solar hardware devices is due to the absence of manufacturing facilities for these goods in the domestic markets**
		End user affordability	When such facilities are introduced to the local community, farmers have a major thorny issue of cost to be able to acquire and incorporate the solar-powered cold-storage technology
		Energy enterpriser	Renewable energy firms themselves do not have adequate capital or fairness available for these farmers to grow their businesses
		Uncompetitive market	Another reason for the lack of decentralized off-grid cold storage is still an uncompetitive market. Since a majority of these systems are created, managed and sustained by private firms, it becomes incumbent on the government to work with

Operational constraints	**Economic**	**High initial cost**	**A solar powered cold storage system costs more than a conventional cold storage system by 30 to 50%. The high price of solar hardware devices is due to the absence of manufacturing facilities for these goods in the domestic markets**
			private enterprise to dismantle market barriers.
	Technical	Energy-intensive process	As compared to other renewable energy technologies like SHL, Agro processing and water pumping etc, cold storage equipment is nearly always switched on and would require more availability of energy. The chillers for small holder farmers are 50-250% more costly than the solar irrigation pumps
		Intermittent nature of solar energy	The biggest drawback of the solar energy is that it is not constant. The irregular behaviour of the sun makes it unfit for consistency hence it is not classified as an efficient source of energy and thus is not suitable for supply of constant power.
		Battery backup	When solar cooling is implemented as a separate system, it costs much since battery backup is generally huge. These batteries have to be replaced after 3–5 years and consumes 30–40% of cost.
		Distribution	Thus due to the young development of sustainable energy technologies farmers have quite limited choices of distributors that can offer installation, spare parts and service. This is due to inadequate skilled manpower.
	Social	Fresh food preference	Some of the industry players and farmers agree with the customer's desire for fresh produce (non-chilled fruits and vegetables) as a potential challenge to the expansion of cold storage.
		Sceptical behaviour	More than a third of the total produce, owned by smallholder farmers, fails to reach the market due to spoilage, before it reaches the farm gate. However, they often question the need for cold storage and the possibility of applying clean energy to run farming machinery.
		Lack of awareness	Thirdly, agriculturalists do not know the availability of new technologies that they can benefit from, particularly those technologies based on renewable energy.
		Scattered community	The energy business faces some challenges; and the distant and dispersed rural populations that are usually very impoverished.
	Environmental	Data availability	This paper seeks to discuss the effects of geographical location in the context of solar energy. Thus, without sufficiently specific feasibility studies, solar systems cannot be fitted. It is also difficult in most developing countries to get adequate environmental information, which are crucial in deploying solar energy.
Opportunities for success	Demand for leafy foods	The shift towards vegetarianism throughout the global population has subsequently driven up the need for fruits and vegetables. To fill this demand, existing losses in the field can be reduced by decentralizing storage facilities.	
	Energy demand	The tapping of new sources of energy has been occasioned by rise in energy demand all over the world. This will likely stimulate the solar powered cold storage market	
		Cooling is the best strategy in the reduction of rate of spoilage; however,	

Operational constraints	**Economic**	**High initial cost**	**A solar powered cold storage system costs more than a conventional cold storage system by 30 to 50%. The high price of solar hardware devices is due to the absence of manufacturing facilities for these goods in the domestic markets**
			adopting cold storage in rural areas of the developing countries has a more serious issue due to lack of reliable electricity.
	Need for food value chain		Absence of proper cool storage is a constraint in most developing countries whereby food loses occur through biological degradation processes and poor farmer returns are almost certain. Floral produce such as fruits, vegetables and diary have high food waste rates due to inadequate cool storage. To enhance sustained nutrition there has to be value chain of foods. This aspect calls for decentralised management of food and food products as described early in this paper.
	Short payback period		This is a problem to farmers because they cannot access financing for upfront payments to acquire the system; off-grid solar makes the system capital intensive. Nonetheless, its short payback period of less than 2 years generates strong business rationale when farmers can obtain the financing facility, thus the cold chain might be adopted in rural areas.
	Agricultural development		Agriculture is one of the most critical drivers of the solar-powered cold-storage business mostly because agriculture is one of the largest consumers of cold storage. A third of the produce produced in the agricultural sector is a result of deterioration. The common causes of produce waste and poor storage quality can be eliminated by solar-powered cold storage that has seen an increase in demand for the facility.
	Business model		The problem with affordability can be addressed with an appropriate business model that meets consumers' needs and expectations and their wallets. Appropriate payment plans could make many low-income consumers take solar items that they regard as very costly. Therefore, measures as if supporting regulation like was lowering the import taxes on parts of solar technology, would have to be important for the solar market and for encouraging more solar service providers to offer and deploy solar technologies. Instead of promoting innovative refrigeration equipment, technology geniuses can create ways that allow charging for cooling as a service. Chilling services would also do away with the need for consumers to take up expensive financing to make the chilling equipment purchases; instead, the chillers would be paid for when such services are needed.
	Awareness of technology		The idea is to make potential users aware of the financial benefits of solar cold-storage technology and to enhance the awareness of the existence and benefits of such technology. Before deploying the system, consumer awareness and sensitization to the technology would be important especially on solar cold-storage solutions to ensure other markets such as consumers buy the technologies besides farmers.

6.2 Economic Barriers

This paper identifies the economic costs of decentralized solar cooling systems as being considerable and multifaceted. Of these challenges, the most compelling one is the capital-intensive cost required on initial installation. Traditional cooling techniques are usually cheaper to install as compared to the modern techniques; therefore, they are easily marketable to the end users particularly the low-income earners. On the other hand, decentralised solar cooling systems … involve capital investments in solar thermal panels or photovoltaic (PV) systems, energy storage systems and new generation chillers. As a result, the initial cost of solar power can turn off many customer from choosing it, especially when there are no short-term gains to gain.

In addition, these systems are relatively cheap, but their availability is normally made worse by poor local production of vital solar equipment. In many regions the technologies have to be imported which adds to the cost because of the charges and tariffs that are involved. For instance, studies have shown that solar powered cold storage facilities can be up to 30 to 50% more costly than conventional ones because of reliance on external supply chain. Besides, conventional funding services available to the consumer who would wish to embrace such technologies are often very scarce, a factor that makes it very hard for many farmers or business people to lay down good cash for the installation of these technologies.

They also add to the overall costs of the decentralized solar cooling systems with regard to their operational costs. While these systems take time to explain the benefits of low ongoing expenses because of the few times they require fuel to maintain after installation, they can be expensive to maintain because they require labor-intensive practices. Maintenance is important in order to get the best out of parts such as the solar panels and batteries. In particular, batteries requiring replacement every 3-5 years create a major cost factor contributing to 30-40% of the total system costs in the course of their lifetime.

Another economic challenge stems from competition in sources of energy and technology that are available in the market. In the places where the cost of electricity is relatively low or subsidized, the demand for conversion to the renewable solutions becomes much lower due to the increased payback periods in comparison with the areas with high electricity tariffs. Such conditions make investments in the technologies unreasonably low despite the fact that they could financially make sense under other scenarios.

However, socio economic factors are also a factor that hampers the use of these systems in the general society. Lack of awareness about the relative value of renewable energy can cause prospective users like farmers a poor understanding that such systems may be useful in their case as there are no successful reference projects to look at. This doubt may be due to culture that does not embrace change and rather prefers to use solutions that are thought to be most tried and tested.

Lastly, there is a dearth of enabling policies targeting such economic issues directly through incentives such as tax relief or grants that seek to address issues of high first costs and low cost of utilization to the consumers. It is possible for the government and companies to engage in partnerships aimed at encouraging manufacture local production and cutting on imports by use of scale economies. See references: [10], [9] and [1].

7. Future Trends and Innovations

7.1 Emerging Technologies in Solar Cooling

New technologies of solar cooling are creating opportunities for the further development of efficient, more sustainable and cost effective solutions that would be able to address the rising demand for cooling in various sectors. Among these, the recent innovation of photovoltaic-thermal (PVT) collectors has substantially integrated both electricity and heat utilizing solar energy. These systems are greatly improve the efficiency by using thermal energy for cooling processes and at the same time generation of electricity to minimize energy problems. The study shows that PVT collectors can produce thermal and electrical efficiencies of 1.9%-22.02% and 0.85%-11% respectively; making them suitable for application in decentralized solar cooling system.

More development progress in the application of solar cooling technology is represented by the use of a combination of technologies including absorption chillers/heat pumps and solar thermal. All these hybrid configurations improve operational flexibility and performance as well as ability to adjust to different conditions. For example, recent investigations have suggested that the integration of transcritical CO2 heat pumps into conventional solar collector systems is highly effective in enhancing system performance, as well as decreasing dependence on external energy.

One more area is the use of machine learning for the improvement of the efficiency of solar cooling systems. These algorithms are able to adjust the operational strategies in real time depending on the data regarding weather patterns, system outputs, and user requirements from large dataset, which drastically enhances efficiency and cost savings.

Radiative cooling techniques are also on the rise as a novel approach within the subsystems of solar energy systems. This passive method incorporates materials that both absorb sunlight and emit heat into the atmosphere and can be added to existing solar configurations to improve their heat handling without requiring extra energy. These techniques not only improve the efficiency of the total system but also reduce the peak load demanded during the times of high power consumption.

The use of smart materials in solar cooling applications has been revealed to have vast potential in enhancing the capability of the solar cooling systems. Such materials may comprise phase change materials (PCMs) to trap or discharge latent heat in response to temperature fluctuations and offer more effective cooling arrangements with less energy.

Moreover, political changes and monetary incentives play a critical role in the implementation of these new technologies in various setting. There is growing awareness globally from governments on the need to incorporate renewable energy and sustainable technologies and this has led governments around the world to offer funding for research activities in the development of innovative solar cooling technologies.

With these technologies integrated together, it is possible to achieve better thermodynamic efficiency, and at the same time, help in the global fight against the use of greenhouse gases in refrigeration. This transformation process still continues in the current century and is a clear sign that the decentralised system, which has the potential to meet the specific needs of a given region while at the same time improving the quality of the physical environment, is gradually being realised [2], [5] and [1].

7.2 Policy Developments Impacting Adoption

Public-policy developments are therefore essential to the spread of decentralized solar cooling systems, as governments worldwide begin to embrace sustainable cooling technologies. As a result, there has been the development of polices, regulations, and incentives towards the deployment of solar cooling solutions.

One emerging trend is the use of rebates, tax credits or grants that assist in cutting down cost of installation. Some areas provide large rebates for solar thermal techniques as well as energy-efficient devices to persuade building owners to abandon conventional cooling techniques. In addition, policies such as accelerated depreciation offer lasting fiscal bail for businesses committing in renewables.

System solutions for integrated urban development are also emerging, for example, cities have included mandatory provisions for solar cooling systems in their building and zoning codes. Insofar as new constructions or new connections to centralized cooling systems incorporating renewable energies such as solar energy are imposed, municipalities can reduce total energy consumption and promote sustainable development.

Decentralized solar cooling technologies are therefore progressively relying on public-private partnerships as the strategy of choice for boosting their deployment. Joint ventures between the different municipal authorities, utilities and private organizations enable joint funding of huge projects where individual funding may be a problem. Modern approaches in financing designs, such as ‘cooling-as-a-service,’ allow the use of enhanced cooling technologies without causing significant initial cost responsibilities.

Changes in policy are also affected by the progress of smart grid technologies when it comes to decentralized solar cooling systems. These systems also have storage options for more flexibility in demand response that improves the stability of the grid at these times. Since grid operators are employing complex coordination techniques, distributed PV based cooling solutions are feasible for energy balancing and decarbonization.

Non-financial barriers are also being tackled through the introduction of educational programs to increase understanding of the potential and capabilities of decentralized solar cooling systems to the major stakeholders and political leaders of municipalities and developers.

At the international level, agreements regarding climate change call for sustainable energy approaches such as decentralized solar cooling as key to achieving the globally set reduction of carbon emissions. Countries that participate in these agreements should establish structures that foster research on, as well as models for, implementation in various settings. Stakeholder engagement will be crucial in fine tuning policies derived from technology and existing evidence where necessary [4], [3] and [22].

8. Conclusion and Recommendations

8.1 Summary of Key Findings

Decentralized solar cooling systems offer a new approach to meeting the growing need for sustainable cooling technologies particularly in areas with high solar insolation. Such system utilize renewable energy resources and considerably decrease dependency on conventional power structures, which are very helpful in cutting greenhouse emissions. Solar powered cool technologies are useful in minimizing post-harvest losses for the horticultural products especially in the developing world where the access to cool facilities is limited. Many studies show that these technologies have enhanced the storage of the food and supported economic performance of foods for smallholder farmers.

Photovoltaic-thermal (PVT) collectors and hybrid solar cooling systems are among the available decentralized solar cooling technologies available. Both systems comprise specific technological subsystems comprising of TES, heat exchangers, and VFDs that improve efficiency and performance. The emerging PVT collectors especially the flat plate PVT collectors have provided promising thermodynamics performance and economic viability making them acceptable for small-scale applications. That is why innovations such as SelfChill technology demonstrate the availability of solar cooling systems for various agriculturally oriented locations, showing the versatility of the approach.

Decentralized solar cooling has major benefits in urban areas for instance, lower energy use and enhanced air quality – by eliminating conventional cooling techniques. In cities, implementations show possibilities in uses in residential infrastructures and commercial complexes, leading to enhanced energy consumption and reduced expenses.

On the other hand, rural implementations bring out the urgency of proper cold storage to prevent losses among farmers who have no efficient ways of storing crops once they are harvested since most of the storage facilities do not have fridges. As a result, solar-powered cold storage can be developed according to the needs of a given region, as well as assist in the growth of renewable energy technology.

However, decentralized solar cooling systems are not devoid of the following difficulties that must be resolved to foster their acceptance. Technical challenges include fine-tuning of systems and hardware layouts, as well as the smooth integration of higher level of system sub-systems such as thermal storage units. There are bound to be economic problems due to the high initial cost of setting up the system and few funding sources for the potential users in the urban and rural areas.

Future opportunities for development within the solar cooling field are anticipated including enhancement of battery systems and its compatibility with other renewable sources of energy such as biomass heating or solar power connection in unfavorable climate conditions. Policy initiatives will also come into the forefront as global governments look for long-term solutions to climate change.

Therefore, there is the potential for the implementation of decentralized solar cooling systems that present a viable sources of efficient food preservation and also have the potential of making a huge contribution towards environmental sustainability goals in both urban and rural areas, [10], [6], [1] & [25].

8.2 Recommendations for Overcoming Barriers to Adoption

In order to encourage decentralized solar cooling systems, a set of recommendations has been developed in response to current issues. One of them is the relatively high first cost that has to be incurred to install and implement these technologies. To reduce this financial pressure, authorities should implement the policy of financial incentives like subsidies or tax credits that can help to decrease the costs at the start-up phase. Further, investing in building new forms of financial instruments could also enhance access for smallholder farmers and businesses such as through blended finance. It may also be worthy of note that some partnerships with the private sector could be used to share the investment responsibilities among different stakeholders.

Promoting a friendly regulatory framework remains crucial in the successful implementation of solar cooling technologies within the existing built environment, both in central and peripheral regions. Government agencies should encourage legislation that compels or promotes the adoption of renewable energy in new buildings and agricultural structures cooling systems. By using this strategy, not only would the technology been encouraged, but consumers' confidence in renewable choices would also have been increased.

One of the major problems is the absence of service networks for the maintenance and servicing of solar cooling systems and in the rural areas where skilled personnel is almost hard to come by. Providing local technicians with the required training and building effective product service networks are the ways to guarantee the stable functioning of such systems. There is a likelihood of enhancing service delivery by engaging businesses and tradespeople within the community apart from creating employment for their members.

Awareness creation processes are crucial to reduce misinformation regarding the efficiency of solar cooling technologies. These campaigns can highlight successful application of these technologies in their use and this can provide confidence to potential users because they will see the long-term economic and environmental gains.

In addition, manufacturers should collaborate on developing package systems that incorporate the solar thermal collectors along with the cooling systems to present a range of simple solutions for consumers. This strategy reduces the design burden to the consumers who may feel pressured to design something they do not know how to.

Investment in research and development in this case should be used to figure out better ways of integrating the system components and to look for better ways of storing energy given the volatility of the energy supply given weather shocks. Thus, it is especially important that enhancements in the storage material or technique will greatly improve the overall efficiency of a heat storage system.

Lastly, performing assessments of the general conditions before the introduction of decentralized solar cooling is also important, and that means carrying out regional research. Overcoming climate constraints by designing for particular climate parameters, specific crop types being stored or specific usage requirements can create solutions that genuinely solve users' problems.

Through the addressing of these various challenges by a number of stakeholders including governments and financial institutions, technology providers, and users, the prospects of wide deployment of decentralized solar cooling systems can be enhanced greatly, [20], [12], [10], [4], [2] and [23].

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