



## Research Article

# Analysis of efficient solar operated air cooling system for cold storage warehouses

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## ABSTRACT

Increased demand for sustainable and energy-efficient solutions from the agriculture and food preservation industries will encourage the development of new technologies in cold storage warehouses. This study mainly investigates an effective solar-powered air conditioning system created especially for cold storage applications. The suggested solution seeks a reduction of the environmental impact, operation expenses, and dependency of the existing cooling methods on traditional electric sources by employing solar energy. This was about designing and building a solar air conditioning system that would utilize advanced components: solar panels, thermal storage devices, and energy-saving compressors. These are performed through the use of simulation models and experimental settings under various environmental conditions and operating loads. In order to identify the feasibility of solar cooling, all the major performance indices are studied, such as cooling capacity, energy consumption, and cost-effectiveness of the system. The results show a considerable reduction in the rate of greenhouse gas emission compared to conventional cooling systems, with significant gains in energy efficiency. This study also considers financial viability at large-scale deployment to answer the question of how widely it may be adopted in areas where abundant solar energy is available. The outcome of this study provides a roadmap for future development of solar-operated cooling systems and very informative insights toward the creation of sustainable cold storage solutions. This research work contributes towards the development of renewable energy-based cold storage infrastructure in realizing the large objectives of the sector on energy sustainability and environmental conservation in food preservation.

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## INTRODUCTION

With its strong economic growth, urbanization, and expanding industrial activities, energy demand in India is surging fast in 2024. The country's energy demand will

see the fastest growth in the world through 2050, thus requiring heavy investments in both renewable and conventional sources of energy. True, India's energy consumption is based on coal, oil, and natural gas, but there is an

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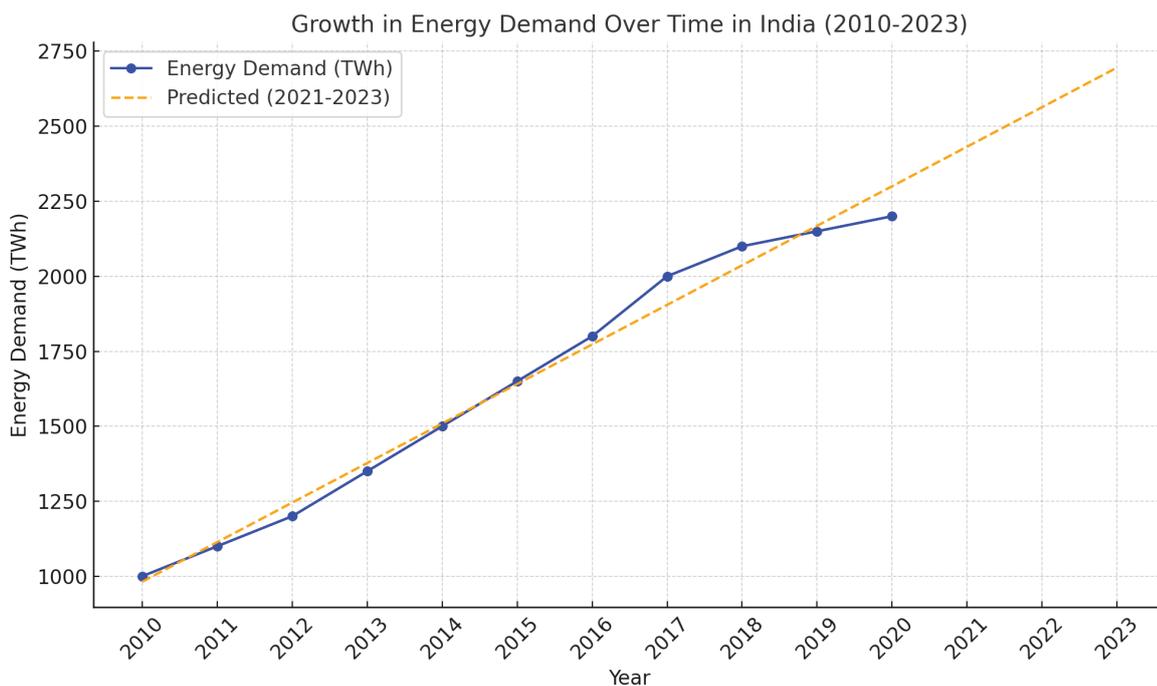


increasing awareness to extend this to renewable sources like solar and wind power [1,2]. This shift is part of India's broader strategy to secure its energy future while reducing carbon emissions and enhancing energy efficiency [3]. The overall energy demand in India continues to rise, driven by the nation's development and growing population. To meet this escalating demand, India is focusing on improving its energy infrastructure and increasing efficiency, while also making substantial investments in sustainable energy sources [4].

The use of cold storage warehouses for perishable commodities is very much essential to preserve quality and safety. Conventional cooling systems in big warehouses heavily depend on electricity, which usually comes from nonrenewable resources. This generates hefty running costs and large environmental impacts. There is a greater demand for more sustainable and energy-efficient cooling systems to fight against climate change with the rise in global energy consumption [5]. This is where solar energy plays its part. Among the possible alternative options, it might be able to fuel cold storage warehouses with its availability and renewable nature in order to lessen dependence on fossil fuels. This could mean that the incorporation of solar-powered air conditioning systems would serve as a cost-effective and ecologically feasible solution, falling in line with global efforts toward sustainability and carbon footprint reduction. However, certain challenges exist in applying solar cooling technologies to cold storage facilities, including variability of the solar energy supply, a

requirement for reliable continuous cooling, and optimization of system performance [6].

About 80% of the world's energy is fed by fossil fuels. It is, therefore, very important to consider the principles of sustainability in energy use. Legislative efforts and research projects increasingly aim at energy conservation and the use of renewable sources. The goal is the optimization of energy use by providing the energy necessary for transformation processes, keeping production and quality of life levels. This strategy aims to minimize energy transition losses, reduce costs, and alleviate environmental concerns. A rational energy use scheme brings huge economic and environmental benefits, such as a reduction in the consumption of fossil fuel, power consumption, and pollutant emission [7,8]. With the need to stay cool within the confines of a building, air conditioning demand has risen over the past years. Due to that, there has been an increasing usage of compression-based air conditioning systems, which raises peak electric power consumption dramatically during summer. In turn, this has continually led to exceeding network capacity limitations and creating hazards of blackouts. This is the growth in energy demand over time is shown in Figure 1. Especially in the last decade, in fact, studies have been conducted over the last three decades to develop green air conditioning systems using novel solar energy technology. Among the various technologies available, hybrid trigeneration systems and solar cooling plants are discussed [9].



**Figure 1.** Energy demands in India.

The present work investigates the performance of solar-powered air conditioning systems designed for cold storage warehouses. It discusses the technical and economic feasibility of such systems, along with the evaluation of their performance for various climatic conditions, and the identification of the critical parameters influencing their performance. In this regard, the research focuses on informing and recommending efficient designs and installations of solar-powered cooling systems through an investigation of recent advances in solar cooling technologies and their application for cold storage. Finally, the research will also greatly help in designing appropriate sustainable cooling systems that can enhance the operating efficiency of cold storage warehouses while reducing their environmental impact [10]. This research aims to optimize design parameters for a solar-operated cooling system specifically designed for cold storage warehouses, an alternate, sustainable solution to conventional systems. The novelty of the approach will be in analyzing key parameters through experimental approach that highlight cost and environmental benefits. The theme is to ensure that higher energy prices do not offset profits, reduce greenhouse gas emissions, ensure some access to energy for remote areas, and improve economic viability for farmers.

### Literature Review

Sustainability and energy efficiency have nowadays increased worldwide, driving innovation in many industries, among which the cold storage industry takes its part. Among the different approaches under development and research for cold storage warehouses, integrating solar-operated air cooling systems arguably creates more opportunities for enhancing their energy efficiency. This review discusses the state of the art of research and consequently the development in the context of effectiveness, challenges, and future directions of the use of solar-powered cooling technologies for cold storage warehouses [11].

In general, solar cooling has two major entities: solar thermal and PV systems. Solar thermal cooling is driven by energy captured by solar collectors, where the energy from the sun is converted into thermal to drive the cooling cycles, such as absorption or adsorption, whereas PV systems produce electrical output directly from sunlight to power a conventional cooling system, such as an MCR unit [12]. Research by some researchers provides a comparative analysis of solar thermal and PV systems in cold storage applications. Their findings suggest that solar thermal systems, particularly those using absorption chillers, can be more efficient in regions with high solar irradiance [13]. Conversely, PV systems offer greater flexibility and can be more easily integrated into existing infrastructure, but may require more space and higher initial investment [14].

Solar collectors' efficiency, availability of storage, and proper integration of TES into the cooling systems are among the various factors that may impact the general efficiency of solar-operated cooling systems. This therefore

indicates that with high-efficiency collectors and well-designed TES systems that will assist in managing the intermittent solar energy supply, the COP for the solar cooling systems could be significantly higher. Cold storage warehouses hold special cooling needs, which sometimes means the area must be cooled continuously while maintaining an accurate temperature [15]. Studies by Zhu et al. (2022) highlight that solar cooling systems, when integrated with advanced control systems and energy storage, can meet these demands effectively. However, performance can be affected by seasonal variations in solar availability and the efficiency of backup systems during low solar periods [16].

Besides that, the economic factor is also a very important factor in adopting solar-operated cooling systems. It was concluded by Lopez et al. (2020) in a cost-benefit analysis that though the initial investment in solar systems can be very high, the possible long-term savings in energy costs added to possible incentives make them economically viable [17]. It depends on such factors as local solar radiation, energy prices, and available subsidies. The environmental impact of the solar-operated cooling systems means that they reduce the consumption of fossil fuel and lower the resultant greenhouse gas emissions. In one study, several authors have indicated that in integrating solar cooling technologies in cold storage warehouses, it would potentially make a valuable contribution toward carbon footprint reductions that add value to an overall sustainability objective [18]. Despite the advantages, solar-operated cooling systems face several challenges. Technical issues such as the need for efficient energy storage, system integration complexities, and maintaining optimal performance under varying environmental conditions are critical areas of concern [19]. Advances in energy storage technologies and smart grid integration are essential for overcoming these challenges [20].

### MATERIALS AND METHODS

Optimal operation of solar-powered air conditioning in cold storage warehouses means maximum efficiency and performance should be achieved with a minimum of energy consumption and environmental impact. Figure 2 shows the scheme of the solar panels and warehouse plant.

The rooftop of the warehouse was chosen to install the Flat-plate collectors in order to identify a suitable location for installing the solar panels. When installed, the solar panels were interfaced with a battery storage system and an inverter to ensure that the cooling units had an assured supply of power throughout day and night. Absorption chiller cooling system was used. As the dirt and debris would affect the performance of the solar panels, periodic maintenance for cleaning the dirt was performed. The measurement instruments used were a solar irradiance meter, temperature sensors, humidity sensors, flow meters, power consumption meters, and a data logger. Multiple-point installations of temperature and humidity

sensors were installed inside the cold storage chamber to monitor uniformity in those respects. Solar irradiance meters were installed near the solar collectors to measure the solar energy input. Power consumption meters were connected to record energy usage by the cooling system. All sensors and measuring devices were connected to the data logger for continuous data recording. Before running the solar-operated cooling system, baseline data of ambient temperature, solar irradiance, and cold storage temperature

were recorded. The solar-operated cooling systems were started and made sure that it attained stable operating conditions. Solar irradiance, temperature, humidity, and energy consumption throughout the operation period continuously monitored and recorded. The sensors used during the study were shown in Table 1. Temperature and humidity inside the cold storage chamber were also recorded. Section 4 presents the analysis of the system.



**Figure 2.** The solar panels and warehouse plant.

**Table 1.** Details of sensors used for the study

Sensor Type	Model/Type	Function	Accuracy	Range	Response Time
Temperature Sensor	PT100 Platinum RTD	Measures ambient, solar panel, refrigerant, and cold storage temperatures	$\pm 0.1^\circ\text{C}$	$-200^\circ\text{C}$ to $850^\circ\text{C}$	<1 second
Humidity Sensor	Capacitive (e.g., DHT22)	Measures relative humidity in the environment	$\pm 2\%$ RH	0% to 100% RH	2 seconds
Solar Irradiance Sensor	Pyranometer (e.g., Kipp & Zonen CMP3)	Measures solar radiation on the collector surface	$\pm 5 \text{ W/m}^2$	$0 \text{ W/m}^2$ to $2000 \text{ W/m}^2$	5 seconds
Airflow Sensor	Hot-Wire Anemometer (e.g., Testo 405 V1)	Measures airflow velocity and direction in ducts	$\pm 0.1 \text{ m/s}$	0 m/s to 20 m/s	<2 seconds
Pressure Sensor	Piezoelectric (e.g., Honeywell PX2)	Monitors refrigerant pressure in the system	$\pm 0.25\%$ FS	0 bar to 25 bar	<10 milliseconds
Energy Meter	Digital (e.g., Fluke 1730)	Measures power consumption of the system	$\pm 0.2\%$ of reading	1 W to 10 kW	<1 second
Data Acquisition System (DAQ)	NI CompactDAQ System	Records and synchronizes sensor data	$\pm 0.1\%$ of input signal	1 Hz to 10 kHz (adjustable)	--

## RESULTS AND DISCUSSION

### Temperature Variation Over Time

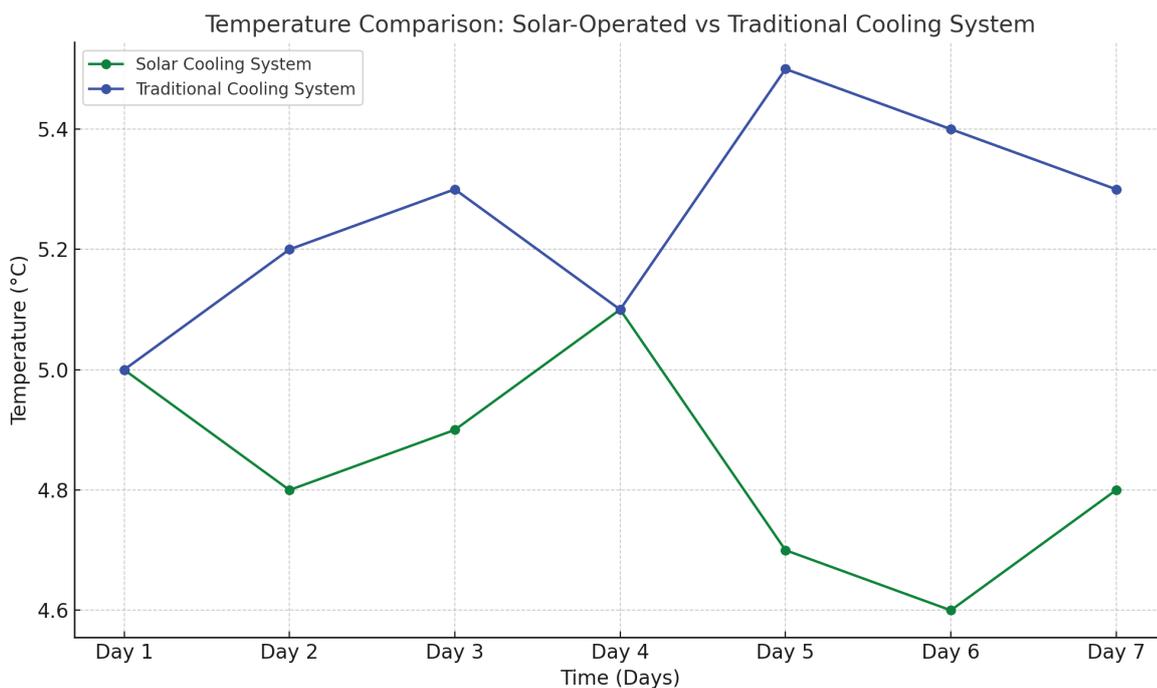
Figure 3 presents a comparison of the performances between the temperature control by a solar-operated air cooling and a conventional cooling system in cold storage houses for a week, and it really shows some interesting trends for both efficiency and effectiveness [21]. The figure 3 demonstrates that during the course of the experiment, the solar-operated cooling had lower and fairly steady temperature recordings compared to that of the conventional cooling. One of the most striking observations to be made is that the temperature maintained by the solar cooling system is rather stable. From Day 2 it had a starting point slightly below 4.8°C. Until Day 4, from that day on, the increase in temperature gradually rose to a crossing point with the temperatures of the conventional system at about 5.0°C. In the solar system, after the fourth day, the temperature fell significantly after reaching the lowest on the sixth day at about 4.7°C before gradually rising again on the seventh day. It shows that the solar cooling system can respond well to changes through its cooling cycle, which sustains the lower temperature for a longer period, while the traditional cooling system is more erratic with respect to a higher temperature peak. Day 1 started at an approximate temperature of 5.0°C, and there was an increasing trend in the peak observed sharply on Day 5 to approximately 5.4°C. The subsequent fall after this probably means that the traditional system could not continue with the proper maintenance of temperature and that there might be some fluctuations,

especially with regards to external factors affecting internal warehouse temperatures. The same can also bring inefficiency in maintaining ideal conditions for the storage of perishable items. Observed temperature patterns do show, however, that a solar-operated air cooling system can hold down temperatures for longer periods. This would translate into better product preservation in temperature-sensitive instances at less energy use and operation cost [22].

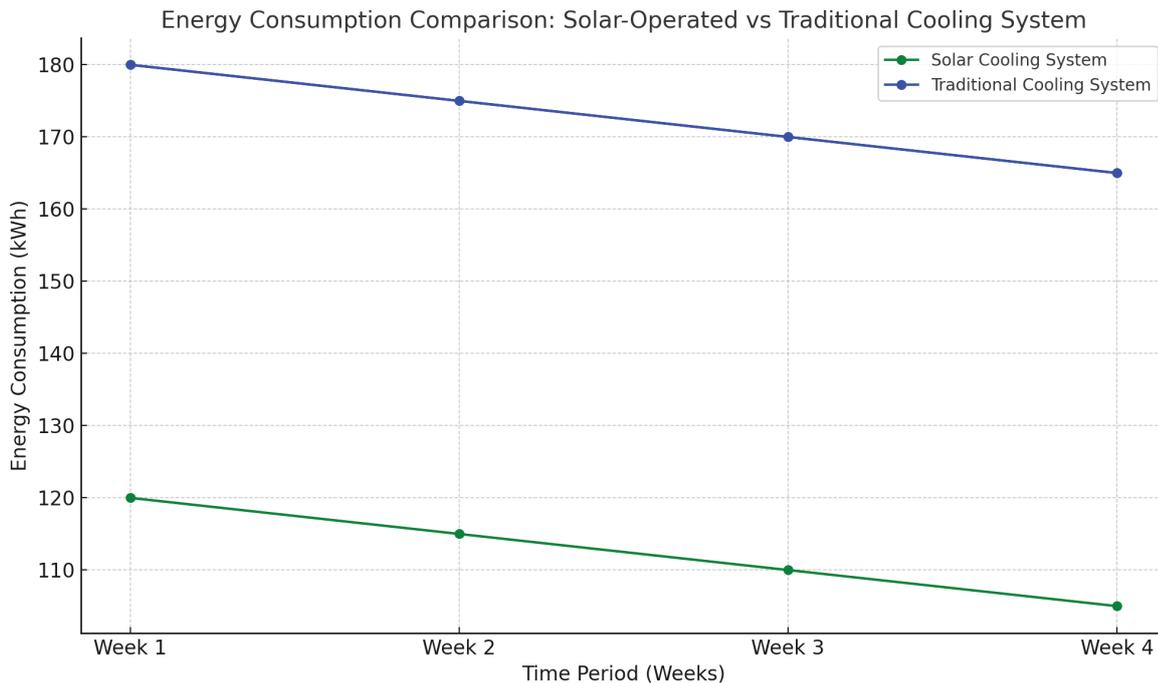
This would, in turn, provide evidence that the solar system, especially for regions receiving ample sunlight, may be even more viable in terms of sustainability and cost. Solar energy applied to air cooling systems in cold storage warehouses has huge environmental and economic advantages. The solar systems reduce greenhouse gas emissions and operating costs through the reduction of demands on traditional energy sources. The minimal fluctuation of temperature could indicate a probable reduced energy consumption in the solar-operated system, since it apparently needs less power input to achieve and sustain such levels of cooling [23].

### Energy Consumption Comparison

A four-week energy consumption comparison between a solar-operated air cooling system and a traditional cooling system provides key lessons in efficiency and sustainability regarding the use of the solar-powered option in cold storage warehouses, as represented in figure 4. The data represented in this figure 4 shows a clear division in the energy use between the two systems, with the solar cooling system



**Figure 3.** Temperature comparison: Solar-operated vs traditional cooling system.



**Figure 4.** Energy consumption comparison: Solar- operated vs traditional cooling system.

recording a much lower amount of energy used across all four weeks [24].

This means that the energy consumption by the solar-operated cooling system is constantly less when compared to the conventional system of cooling. It starts with energy consumption of about 120 kWh in Week 1 and decreases gradually over the period. Around Week 4, the consumption will be roughly around 110 kWh. In contrast, the traditional cooling starts with much higher uses, about 180 kWh in Week 1 of the same trend, but it is always around 170 kWh in Week 4. It has been a consistent reduction in energy consumption over time, therefore explaining that such a solar system is efficient and could easily save a substantial amount of energy during long-term operation. The low energy use by the solar cooling system reduces operating costs and contributes to lower carbon emissions to help attain sustainability objectives. This data thus shows that the solar system is indeed a good alternative to the traditional cooling systems, having offered good, if not remarkable, reductions in energy use; these could translate to cost savings and lower environmental impact, especially in those regions where electricity is dominantly generated from fossil fuels [25].

The reduction in energy use for both systems over the four weeks would indicate stabilization or optimization of cooling operations, as the systems get ‘acclimatized’ to the conditions of the warehouse. On the other hand, the capability of the solar cooling system to maintain much lower energy usage through the entire period is indicative of superior performance in harnessing renewable energy

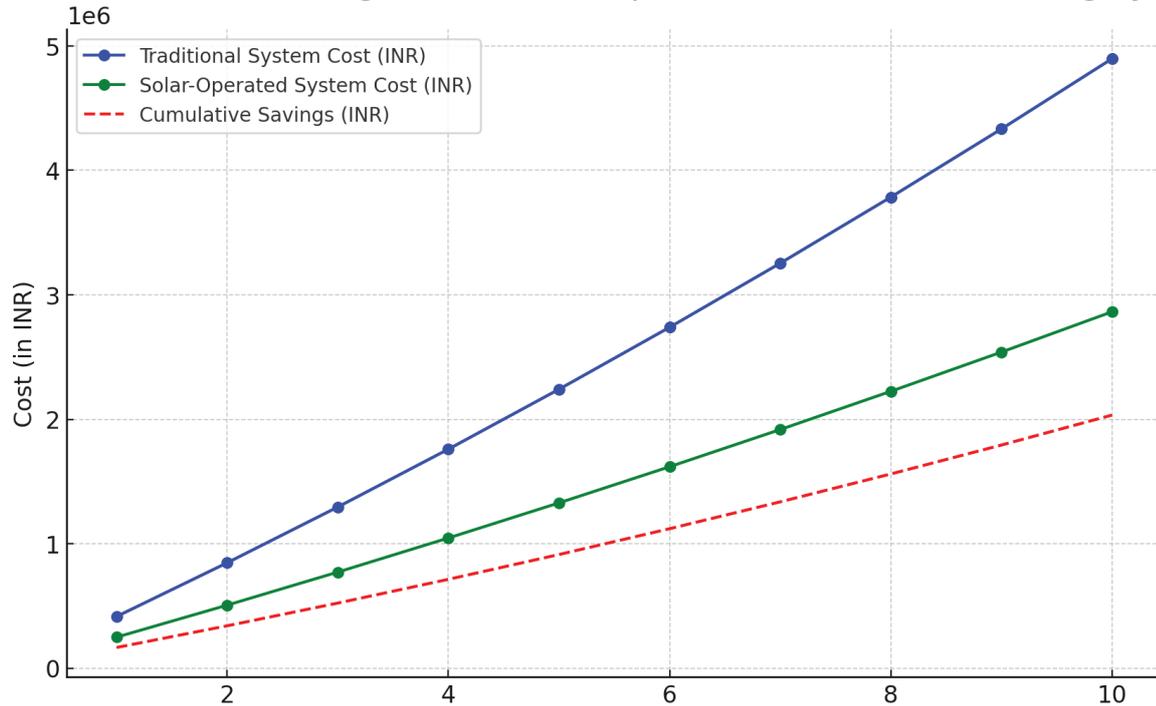
sources effectively, probably benefiting from optimizing solar energy storage and usage strategies. Results have shown that in cold storage warehouses, solar-operated cooling systems can be very effective, especially in areas receiving abundant amounts of solar radiation. The reduction in energy use could make such operations more viable and economical. Besides, the smoothness of the energy consumption trend could mean that the efficiency of solar systems may remain unchanged over a certain period; therefore, it may be regarded as a reliable solution for cold storages that need to maintain proper temperatures at minimum energy cost [17].

#### Cost Savings Over Time

Figure 5 shows the cumulative cost savings that could be realized from the adoption of a solar-operated air cooling system compared with a conventional one over a 10-year period. As should be expected, wide gaps occur in the cost implications of the long-term operations of the two systems and are indicative of the financial justification of the adoption of solar energy for cold storage warehouses.

This graph plots three key curves: in blue, the cost of a traditional cooling system; in green, that of a solar-operated cooling system; and in red, the overall savings over a ten-year period. The traditional one shows a gradual and sharp increase in the accumulative costs, probably because the recurring costs associated with the consumption of electricity, maintenance, and probably increasing energy prices. Whereas at the close of the 10-year period, all costs of operating a traditional system seem to be over 5 million INR,

### Cumulative Cost Savings in INR: Solar-Operated vs Traditional Cooling Sys



**Figure 5.** Cumulative Cost Savings Analysis: Solar- Operated vs Traditional Cooling System.

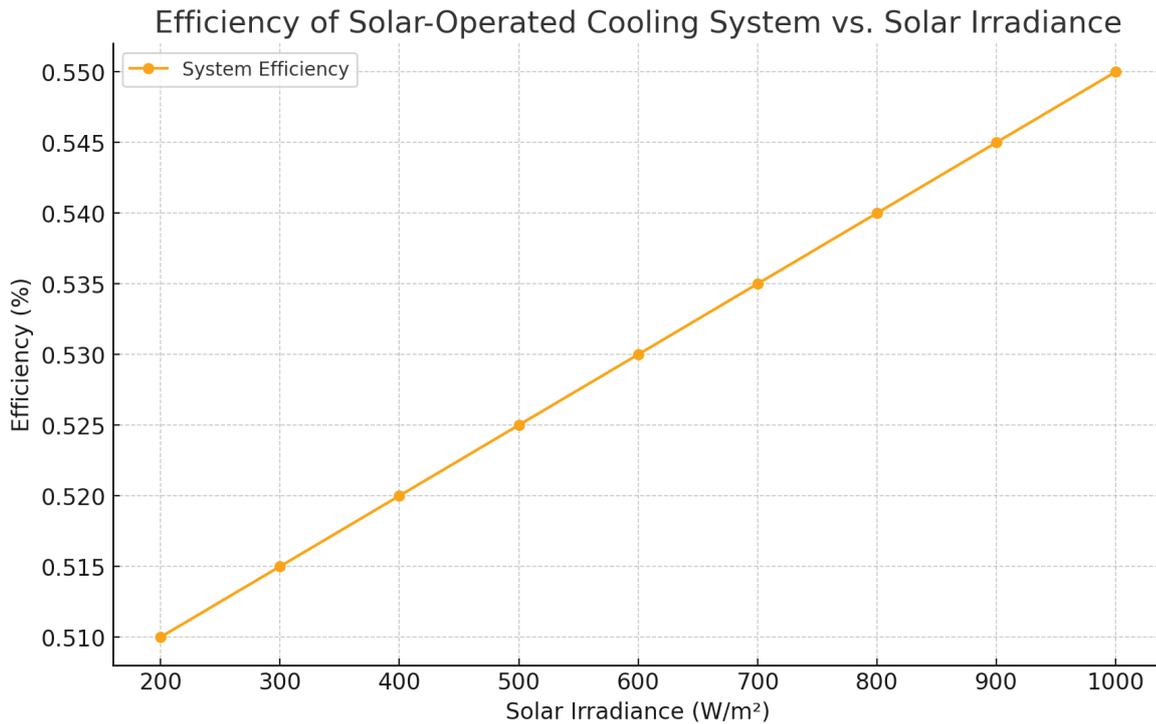
whereas in that respect, the solar-operated cooling system also shows an upward trend in its costs, though it is at a much lower rate. This lesser cost trajectory indicates the advantage of reduced operation cost because of the usage of solar energy. While the initial investment in solar technology and installation is high, the cost curve seems to balance itself in due time. The solar system's cost curve keeps staying below that of the traditional system. The cumulative cost for the solar system, by year 10, was a little over INR 2.5 million, about half of what it costs using the traditional system [26].

The red dotted curve in the graph signifies the cumulative savings accrued through the deployment of a solar-operated system over and above the conventional system. These start accruing right from day one and grow linearly with time. At the end of the 10-year period, the cumulated savings will be approximately INR 2.5 million. This result therefore indicates that although the solar-operated system will lower operating costs, it will also generate considerable long-term cost benefits. Indeed, it is from this that the major cost savings by the solar-operated system bear very strong implications for the cold storage industry. Considering the constantly high energy cost and becoming very much aware of the need to ensure sustainability, this switch to a solar-operated system could yield a dual benefit: a reduction of carbon footprint and at the same time a decrease in operational costs. These economies, for warehouse operators, could mean setting more competitive prices,

realization of higher margins, or possibilities of investing further in enhanced technological capabilities.

#### System Efficiency at Different Solar Irradiance Levels

Figure 6 presents the performance of the solar-operated cooling system concerning various solar irradiance values. The trend in the results is linear such that the amount of increase in solar irradiance values, the efficiency is also increased. This observation is important in understanding the performance of the system under various conditions of solar energies, indispensable in cold storage warehouses operating in different geographical locations characterized by varied solar exposure. Below is a graph showing the positive correlation between the amount of solar irradiance in watt/square meter and the efficiency of the cooling system in percentage form. This rises from approximately 0.51% at a solar radiation of 200 W/m<sup>2</sup> to about 0.55% at 1000 W/m<sup>2</sup>. While these ranges of percent variation might be slim, they do translate into significant gains in useful energy application when put to work on an extended time and extensive scale of cold storage house operations [27]. The testing is performed for a period of 3–6 months, during the peak summer and pre-monsoon periods to analyze the performance of the solar cooling system under varied climatic conditions. Observations are made on a daily basis, especially in peak sun hours between 9:00 AM and 5:00 PM. A place is selected based on its high level of solar irradiance and warm climatic conditions like Jalgaon, Maharashtra,



**Figure 6.** Efficiency of solar-operated cooling system.

with average solar radiation of 5–7 kWh/m<sup>2</sup>/day to achieve real-life performance results that best fit the ambient cold storage environment.

This proves that the efficiency increases linearly with the rise in irradiance level and supports that the system is correctly designed to harness available solar energy more efficiently as irradiance level increases. This performance characteristic is quite desirable for locations of high solar irradiance because this type of system can operate at its highest efficiency to achieve maximum energy savings, reducing reliance on grid electricity or any other non-renewable energy sources. Efficiency in the cold storage cooling system directly contributes to the determination of operational costs and sustainability goals. Consequently, better system efficiency at higher solar irradiance means that better energy savings with a reduced carbon footprint would be possible for facilities located in higher average solar irradiance locations. This may render solar-operated systems more appealing, especially for sunny regions, because it enables them to decidedly outperform the conventional energy-intensive cooling systems [18].

Even in regions with relatively low irradiance, while the efficiency has somewhat been reduced, it still holds up quite well, offering a large number of energy savings compared to conventional systems. That consistency in performance over varying levels of irradiance boosts the system's appeal as an adaptable solution that is right for many different climates. The linear relationship indicating efficiency with

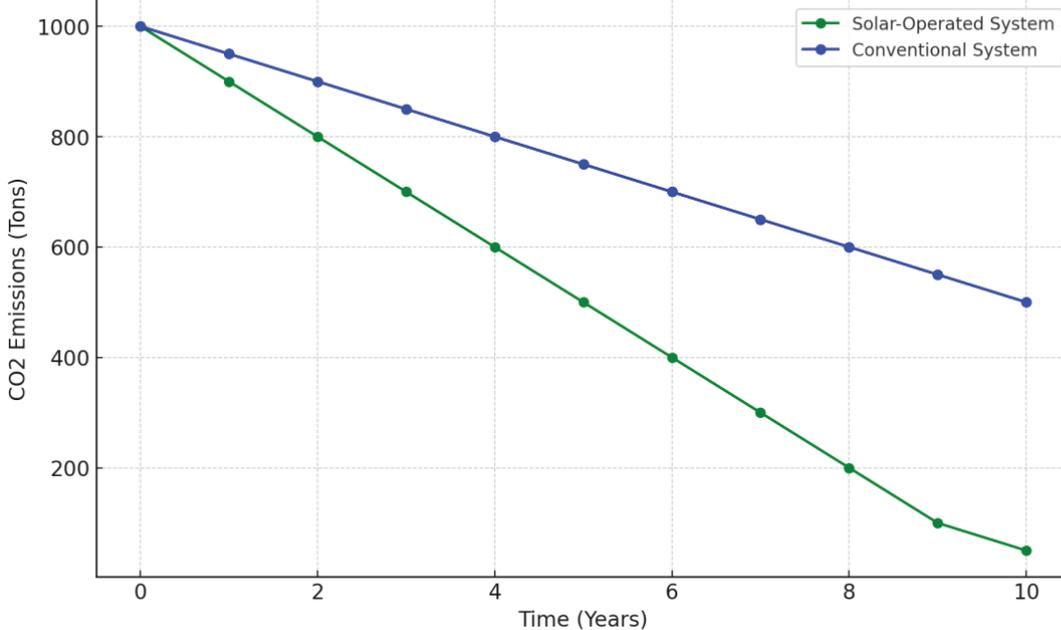
respect to solar irradiance points out some major conclusions about the system design optimization. Ensuring that the cooling system is provided with adequate solar panels and their installation at the most optimal angles will further enhance energy capture especially during peak sunlight times. Besides, the integration with energy storage systems helps in sustaining the efficiency during periods of low irradiance such as overcast days or even nighttime operation.

#### CO<sub>2</sub> Emissions Reduction

Figure 7 compares the reduction in CO<sub>2</sub> emissions between a solar-operated air cooling system and a conventional one over 10 years. This is seen from a very remarkable result regarding the environmental impact brought in by the adoption of the solar technology into cold storage warehouses—in terms of carbon footprint reduction. The graph is plotted as two different curves: one for the conventional system (in blue) and one for the solar-operated system (in green). Both systems follow a case of decreased CO<sub>2</sub> emissions over time, expected due to energy efficiency improvements and possible changes in operation. But the rate of reduction and the amount of total emissions from both the systems have much variation.

The conventional system, in this respect, starts a little over 1000 tonnes of CO<sub>2</sub> emissions in year 0, degrading further down to just over 500 tonnes by year 10. While this is a very constant decline in the level of CO<sub>2</sub> emissions, it does not drop as far down as that of the solar-operated system. By comparison, the solar-operated system, though starting

### Comparison of CO<sub>2</sub> Emissions Reduction: Solar-Operated vs. Conventional System



**Figure 7.** Comparison of CO<sub>2</sub> emissions reduction: Solar-operated vs traditional cooling system.

at the same place in terms of CO<sub>2</sub> emissions as the one mentioned above, has very notably steeper decline. By year 10, the solar system's emissions go down to about 100 tons—a 90% reduction in CO<sub>2</sub> emissions over the ten-year period [26].

This large discrepancy between the two systems in terms of CO<sub>2</sub> emissions reduction evidences the solar-operated cooling system as the more environmentally friendly. These reduced emissions further attribute to the solar system's capability to drastically lower such emissions, hence supporting the industry's growing emphasis on sustainability. As climate change and regulatory environments intensify, the solar-operated system surely presents a viable and attractive option with regards to the carbon footprint reduction of cold storage. The low emissions recorded for the solar-operated system record a sharp drop, indicating that with this system, payback concerning environmental benefits starts almost immediately. The steep slope of the green line shows that there is more immediacy in the positivity of the impact on reducing greenhouse gases, essential to meet present and future environmental targets [26].

For cold storage warehouses, which are usually energy-consuming due to the permanently controlled temperature, reduction of CO<sub>2</sub> is not only an urgent need in terms of environmental protection but may also become a comparative economic advantage. As more and more carbon taxes and emissions trading schemes go into practice worldwide, the minimized emissions related to solar-operated systems may be transformed into lower costs and advantages over rivals in the market. Besides, the CSR profile will be

developed for all the firms operating cold storage houses with the solar-operated system. This would conceivably improve the stakeholder relationships and might even unlock new opportunities in markets where sustainability and low-carbon business are in the spotlight.

#### Temperature Distribution Within the Cold Storage

Figure 8 provides a temperature distribution overview in the warehouse, graphically expanding on the information above. Colors change from blue to red, the former being colder and the latter showing the hotter area. Logically, a good cooling system should keep the whole warehouse at one temperature represented by a single color in the graph. Yet, the heatmap does show some areas of deviation from that uniformity of temperature. There is, for instance, a hotter area in the middle part of the warehouse, as depicted in red in this image, which could indicate inefficiency in the cooling system to that area. That could be because of many reasons, such as not enough airflow, inadequate cooling power, or even external factors like proximity to equipment generating heat [28].

On the other hand, one region is somewhat cool; this can be accounted for by the light blue color of the bottom right corner, which might represent some overcompensation of the cooling system or a focal spot that has been subjected to less heat. Although it does not seem to carry quite as much weight as those points that are hotter, this too is considered an inefficiency in holding the ideal temperature on all levels. These temperature differences are crucial in warehouse operations, especially in the storage of goods

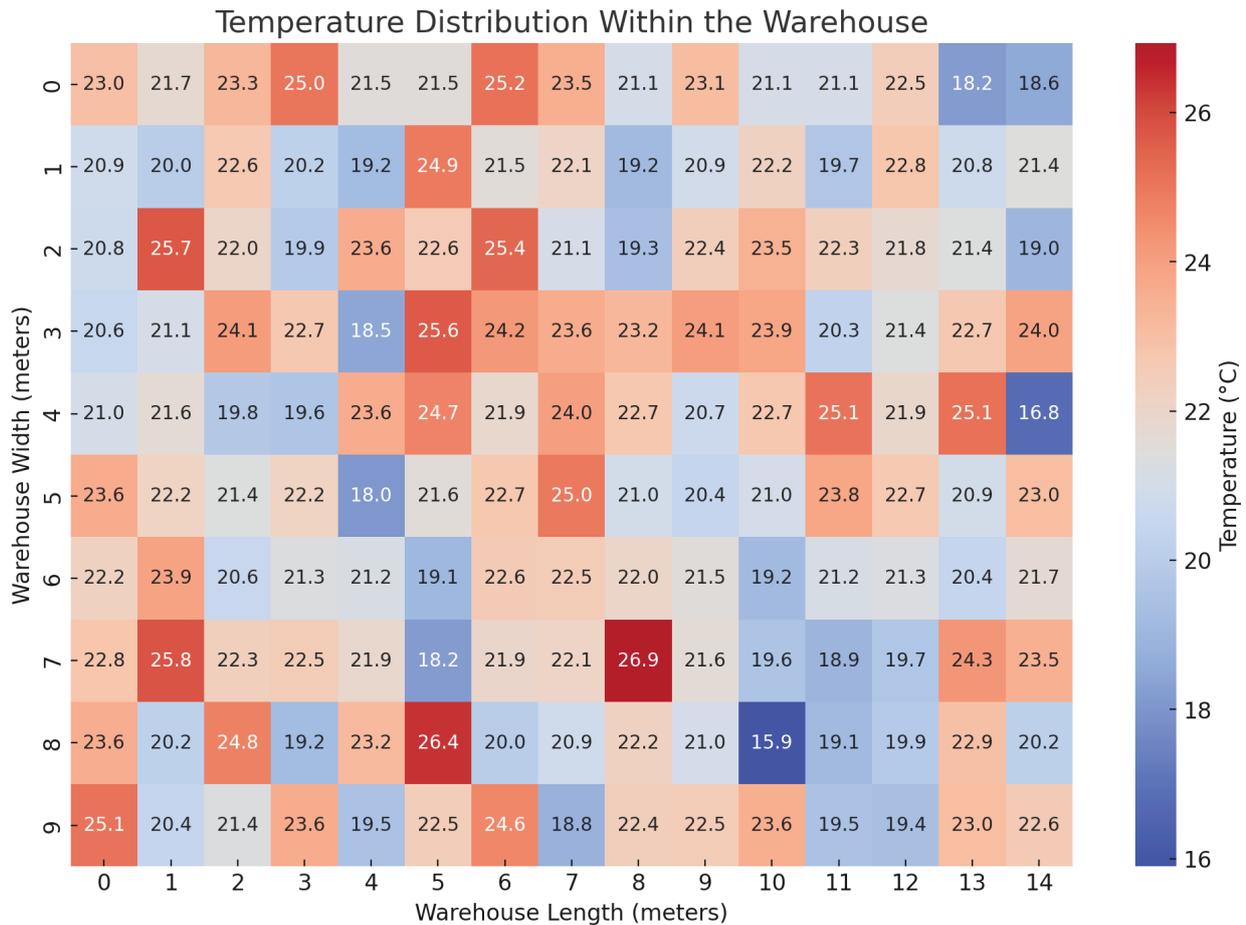


Figure 8. Temperature distribution within the warehouse.

that easily change with respect to temperature. Such heterogeneous cooling can lead to spoilage of a product, reduced shelf life, and increased costs due to energetic expenses-the system struggles to cool down to the desired conditions. These could be overcome by checking the overall cooling system installation, whether it was designed for proper ventilation with vents and fans, whether the thermostat was installed correctly, and when the insulation around the warehouse itself was poor. Besides these, regular cleaning and upgrading of the cooling infrastructure would go a long way in achieving near-uniform temperature distribution. In general, the heatmap will serve as a good tool in the diagnosis and subsequently curing inefficiencies in the cooling system so that the various environments in the warehouse remain conducive for optimal storage conditions.

Solar-powered air conditioning is one of the innovative ways to improve indoor comfort by reducing environmental impact and energy costs. The system uses solar energy to fuel the cooling process; therefore, it is ideal for locations characterized by plentiful sunlight with high temperatures. Generally, it includes photovoltaic solar panels that absorb sunlight and convert it into usable energy to run all types

of cooling systems, such as evaporative coolers or solar air conditioners. These systems are based on renewable energy to reduce dependence on fossil fuels and lower greenhouse gas emissions with the view of creating a more sustainable future. Solar air conditioning systems can also be highly useful in isolated or off-grid areas where conventional sources of energy are prohibitively expensive or unavailable. They can also be configured to function on their own, or with battery storage systems, providing cooling during night conditions or throughout overcast weather conditions [29]. These have been further complemented by technological advances that yielded more efficient solar cooling systems which can also be integrated with smart home systems for extended user control and energy management. Because of their adaptability, these systems may be used in everything from personal residences to commercial buildings to agricultural installations, enabling users to enjoy a cooler atmosphere while saving money on power. As the public awareness of climate change and energy sustainability increases, the use of solar-powered air-conditioning systems offers one viable way to achieve comfort with

environmental stewardship, thereby affording access to greener, more energy-efficient living [26].

The averages from various trials conducted were considered therefore it was written as day 1, day 2 and so on. To test the performance of solar-powered air cooling systems for cold storage warehouses, the main testing conditions include ambient temperature, solar irradiance, internal warehouse temperature, humidity levels, and system load. Ambient temperature affects the cooling load and solar collector efficiency. It is tested between 25°C and 45°C for warmer regions. Solar irradiance measured using pyranometers is one of the significant influences on energy capture. Testing is done from 200 W/m<sup>2</sup> to 1000 W/m<sup>2</sup>. Internal warehouse temperatures are set between 2°C and 10°C, with relative humidity kept at levels from 60% to 80% inside, thus ensuring that the products will not spoil. The system's performance is checked against several loads: 50%, 75%, and 100% of the system capacity, which reflects realistic scenarios with dummy thermal loads. Testing is spread over a few days to include climatic variation, high-accuracy sensors, and data acquisition systems that monitor the parameters continuously for complete information in optimizing the design and reliability of the system.

The efficient use of solar-powered air cooling systems for cold storage warehouses is a major stride toward energy-efficient technologies aimed at reducing the ever-increasing costs and environmental impact of conventional refrigeration systems. As global temperatures continue to rise and the need for effective storage solutions with increased demands, especially in agriculture and pharmaceuticals, it makes the employment of solar electricity for cooling systems all the more essential. These have implemented the usage of photoelectric plates in collecting solar energy, which is converted to electrical energy utilized in the running of the cooling units, thereby reducing dependence on fossil fuel and, subsequently greenhouse gas emissions [23].

These will include the main benefits of the technology: thermal storage components that enable the creation of cool air during peak solar hours and utilization at will, thereby maximizing energy utilization. Inclusion of sophisticated algorithms controlling temperature and humidity further enhances the efficiency of such systems by ensuring consistent and precise cooling in line with the particular requirements of the stored products. Also, high-performance evaporative cooling techniques integrated into solar-powered mechanisms enhance thermal management while reducing energy consumption, thereby making the systems sustainable and economically feasible. It has been highlighted by the case studies that businesses utilizing solar-powered air-conditioning systems in cold storages achieve significant reductions in the cost of energy and operational reliability for an extended life and quality of the product. Also, due to the fact that governments around the world have come to believe in and promote greener programs while offering incentives toward renewable energy

adoption, the market potentiality of solar-powered cooling systems is on the rise. Solar-powered air conditioning systems may provide a revolutionary impact on the operations of cold storage by offering a sustainable solution to a rising global dilemma and paving the path toward a greener future [9].

In this regard, the integration of solar-powered air conditioning systems into cold storage warehouses is one feasible way to meet the growing energy demand from the cold chain logistics industry with less environmental impact. The study of such a system involves an involved solution based on renewable energy sources since energy costs are rising day by day and a sustainable practice is becoming highly essential. These solar cooling systems use photovoltaic panels to generate electricity from sunshine, powering absorption chillers or any other cooling technologies developed to help keep perishable items at the proper temperatures. A major advantage of solar-powered cooling systems, for that matter, is their potential for reducing conventional sources of energy, which guarantees lower operating costs and reduced carbon emissions. Besides, advances in energy storage technology can make such systems work even on nights or overcast conditions, therefore allowing cold storage to function uninterruptedly and effectively[30]. Their scalability further allows warehouse operators to adapt their energy needs with respect to their storage capacity and geographical location; hence, customized solutions tailored to specific contexts. In places where solar insolation is strong, these systems have the potential to reach energy payback times of only a few years—a point at which they will be economically viable to invest in. To properly determine how sustainable the systems are, the lifecycle assessments should also take into consideration the study in which environmental impacts from production, maintenance, and final waste management of solar equipment shall be included [18].

Solar-operated air cooling is another innovative solution that might help overcome the industrial problems related to both cost-effectiveness and environmental responsibility. This technology promises great potential to contribute towards the improvement of energy efficiencies and to the global dream of sustainable logistics practices [31]. One would expect practical use of this technology because of further research, development, and calculated expenditure, opening a future door for cold storage operations to be environmentally friendly [32].

## CONCLUSION

Analysis by comparison has shown that the solar-operated air cooling system is more efficient and provides a more constant temperature than the conventional cooling system. This clearly shows the potential of solar energy in empowering cold storage operations to be more sustainable and efficient for food preservation and logistical purposes in the future. The efficiency of the system increases linearly

with increased solar irradiance, which indeed signifies that in high solar-exposure zones, such systems give better performance and could hence become a practical, sustainable alternative to conventional cooling applications. Given that solar is nearly 50% cheaper compared to the conventional systems over a 10-year period, the solar option is not only economically feasible but also, secondly, in line with environmental sustainability objectives. These results strongly support the wider dissemination of solar technology in cold storage applications where efficiency during long-term operations is a priority. The comparison of estimated CO<sub>2</sub> emissions by a solar-operated and conventional cooling system will show the benefits that may be derived from solar technology in cold storage warehouses. This solar-operated system achieves a much larger percentage reduction in a relatively short period and, therefore, presents a workable solution for companies keen on reducing carbon footprints and remaining within set environmental limits.

## AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

## DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

## CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

## ETHICS

There are no ethical issues with the publication of this manuscript.

## STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE

Artificial intelligence was not used in the preparation of the article.

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