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A Review on Solar Powered Cold Storage Integrated with Thermal Energy Storage

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Abstract : This review paper discusses various aspects of solar-powered cold storage with thermal energy storage backup. The paper provides insights into the development and designing of solar-hybrid cold storage systems for on-farm preservation of perishables. It covers the guidelines for testing set up and testing procedures for solar cold storage with thermal storage backup, specifications and requirements for the solar cold storage with thermal energy storage backup, and the technical designing of stand-alone solar photovoltaic and solar thermal driven cold storage unit with thermal storage system. The paper also presents economic analysis and feasibility, IRR, NPV, and Payback for different possible business models. Additionally, the paper covers the use of a solar-powered battery-free refrigerator with a cold thermal bank, the design and thermal analysis of a solar-powered cold storage warehouse using a phase-change material, and the design and test of an affordable cold room powered by solar. The study also evaluates the intervention to install solar-powered cold storage in northeast Nigeria, provides evidence from the evaluation of recent interventions in northeast Nigeria, and highlights the barriers impeding the deployment of solar-powered cold storage technologies for post-harvest tomato losses reduction. Finally, the paper presents the performance analysis of a household refrigerator integrating a PCM heat exchanger.

IndexTerms **– Solar Powered Cold Storage, Thermal Energy Storage.**

1. Introduction:

The world is facing an increasing demand for food due to the rapid growth of the global population. The post-harvest loss of perishable food items is a major problem that has been causing serious concerns among policymakers, farmers, and researchers. Inadequate storage facilities and infrastructure are some of the factors that lead to the wastage of perishables. Moreover, the conventional methods of storage, such as cold rooms and refrigerators, consume a large amount of energy and are expensive to operate, especially in rural and remote areas.

In recent years, solar-powered cold storage with thermal energy storage backup has emerged as an alternative to traditional storage methods. This technology has the potential to address the challenges of food preservation and storage, especially in off-grid and remote areas. Solar-powered cold storage systems use renewable energy from the sun, which is abundant in many regions, to power the refrigeration cycle. Thermal energy storage (TES) backup systems are also used to ensure that the stored items remain cool during periods of low solar radiation.

This literature review paper aims to summarize the recent developments and advancements in solar-powered cold storage with TES backup technology. The paper discusses various studies that have been conducted on this technology, including design, fabrication, and testing of solar-powered cold storage systems. The paper also highlights the benefits of solar-powered cold storage systems, such as reduced energy consumption, cost-effectiveness, and improved shelf-life of perishables. Finally, the paper identifies the challenges and barriers to the widespread adoption of solar-powered cold storage systems and proposes some possible solutions.

2. Design of Solar Powered Cold Storage with Thermal Energy Storage

Munir et al. (2021) have developed and designed solar-grid hybrid cold storage system for on-farm preservation of perishables. Computational Fluid Dynamic analysis was performed to assess airflow and temperature distribution inside the cold chamber. They have concluded that 225L brine solution TES maintained the temperature of the cold storage chamber with 2000 kg potatoes at 7°C for more than 12 h with a 5 °C rise in temperature.[1]

Ashish et al. (2020) have designed small-scale cold storage for perishables which is capable of saving the perishables of the small farmers on a personal basis. It has been found that Cold Storage (5 MT capacity) coupled with PV power plant and battery bank can reduce 622.78 kg CO2 emission annually. [2]

Sahoo et al. (2019) have attempted the technical designing of stand-alone (off-grid) solar photovoltaic and solar thermal driven cold storage unit with thermal storage system since the Stand-Alone PV system has been shown to be reliable and cost effective for cooling and refrigeration and has attracted users. Economic analysis such as feasibility, IRR, NPV and Payback for different possible business models is also presented by them. They found that the photovoltaic system with thermal energy storage is shown to be more effective in the aspect of ease in design, availability of technologies, higher NPV and faster payback period. [3]

Bharj and Kumar (2015) designed, fabricated and developed low power air conditioning system using PV modules for a specific application with an estimated requirement of cooling in cold storage. Stand-alone PV systems have shown to be reliable and cost

effective for cooling & refrigeration and have attracted the users. They have also deal with experiences encountered including the successful operation of the refrigeration system during off the sunshine hours continuously for 7 or 8 hours. [4]

Nantambi and Namazzi (2019) have designed and tested a Cold Room powered by solar for improving storage quality and reducing wastage of horticulture produce. The testing revealed that reusing plastic waste PET bottles filled with air as insulation material for cold rooms can save energy, a good innovation for developing countries in the climate change error. Test results showed that the designed low cost cold room powered by solar can extend shelf life of fruits and vegetables. This will therefore increase the revenue period for smallholder farmers as well as their bargaining power in the market place. [5]

Huang et al. (2015) designed solar air conditioning system directly driven by stand-alone solar PV. The air conditioning system will suffer from loss of power if the solar PV power generation is not high enough. It requires a proper system design to match the power consumption of air conditioning system with a proper PV size. They experimentally investigated six solar air conditioners with different sizes of PV panel and air conditioners which were built and tested outdoors to the running probabilities of air conditioning at various solar irradiations. The air conditioner is driven directly by solar PV module through an inverter. No grid power is connected. In order to balance the solar PV power and load power and reduce the cost, a small buffer battery is installed. Hence, the air conditioner may suffer from loss of power which can be characterized by two variables, instantaneous operation probability (OPB) and daily overall runtime fraction (RF). [6]

Beldar et al. (2021) have designed cost effective and low energy hybrid cold storage which is capable to store post-harvest products of the small farmers on a personal basis. The energy required by hybrid cold storage is supplied by electric supply of local utility and photovoltaic power plant and battery system. Apart from design they have analyzed how the use of compound insulation system improves the efficiency of cold storage. Their design is easy to construct and needs small number of peripherals which makes it cost effective and energy efficient. The automatic controlling of the cooling system makes it more users friendly. [7]

3. Government Guidelines for Testing:

The Ministry of New and Renewable Energy (MoN&RE) (2021) has developed guidelines for testing of solar cold storage with thermal energy storage backup.

The MoN&RE guidelines specify the testing procedures, methodologies, and performance parameters that need to be considered while testing solar thermal energy systems. These guidelines also provide recommendations for selecting suitable test facilities and equipment, as well as guidelines for data recording and reporting.

Specifications and Requirements for Solar Cold Storage with Thermal Energy Storage Backup:

5 MT storage capacity – 125-175 MJ TES

10 MT storage capacity – 250-350MJ TES[8]

4. Experimental Analysis

Pinto & Madhusudhan (2020) investigated solar powered battery-free refrigerator, with use of cold thermal bank, to provide cooling at night. From experiments they concluded that TES of water & ethelyne glycol of 10 liters can provide cooling for 17 hours under full load condition for refrigerator of 150 liters capacity. [9]

D.C. Onyejekwe (2012) analyzed the physiro-chemical problems inherent with a phase change material for a desired cyclic performance and gives the thermo-physical properties of NaF/N2O eutectic mixture used for the analysis in ware house. They found from prototype of the system that Temperature of the ware house remained at 1°C for 16 hours using PCM. [10]

Takeshima et al. (2021) have evaluated an intervention to install solar-powered cold-storage in northeast Nigeria. Using these cold storages led to a significant increase in horticulture products sold and profits earned by marketagents, while significantly reducing the share of products lost or wasted before sale. They have filled this knowledge gap by providing evidence from the evaluation of recent interventions in northeast Nigeria in which 7 small solar-powered cold-storages were installed across 7 horticulture markets. [11]

Elarem et al. (2017) have experimentally investigated a household refrigerator to improve the energy efficiency of by integrating a Phase Change Material (PCM) to accumulate thermal energy and stabilize the temperature in the refrigerator compartment. They concluded from experiments that the power consumption of the household refrigerator with PCM heat exchanger is reduced by 12% and the COP is increased by 8% compared to the refrigerator without PCM. [12]

Evans et al. (2013) optimized cold storage in terms of heat loads and the operation of refrigeration system. The results has shown that considerable energy savings can be achieved in cold stores. Results from 38 cold store audits carried out across Europe. The majority of the savings identified had paybacks of less than 3 years. The overall result of this study demonstrates that generic advice is of limited use to cold store operators. Each cold store must be assessed individually to fully optimise performance and to maximise energy savings. [13]

Wang et al. (2017) investigated an off-grid PV cooling system with combing Battery Storage and TES and the influence of battery efficiency, tank insulation and chiller schedule on system efficiency and storage capacity. The results have indicated that, in comparison with Battery Storage and TES, the proposed TES can rise system efficiency by 6.73% and 10.27% under convex cooling load while by 7.16% and 10.50% under ascending one. [14]

Basediya et al. (2011) reported basic concept and principle, methods of evaporative cooling and their application for the preservation of fruits and vegetables and economy. Thus, the evaporative cooler has prospect for use for short term preservation of vegetables and fruits soon after harvest. They found that approximately 23–35% of the horticulture produce goes waste due to improper post-harvest operations and due to lack of enough storage facilities. Evaporative cooling system have a very large potential to propitiate thermal comfort. [15]

5. Numerical Analysis

Pavithran et al. (2020) investigated the effect of PCM incorporation in refrigerator by numerical simulation. The CFD simulation methodology was taken to predict the results. The objective of the work is to analyze the effect of PCM incorporation in the refrigerator, for that different configuration arrangement of PCM in refrigerators were taken for their work. PCM with horizontal, vertical and combined configuration is simulated and concluded that combined configuration is best for stabilize temperature inside cold room. [16]

Azzouz et al. (2007) simulated the effect of adding a phase change material (PCM) slab on the outside face of a refrigerator evaporator. They experimentally validated a dynamic model of the vapour compression cycle including the presence of the phase change material. From results they concluded that by adding a PCM slab on outside slab of evaporator CFD model predicts 5-15% enhancement in COP. Experimental tests with PCM with a melting temperature of -3°C have confirmed these results. [17]

Maeques et al. (2013) have modeled and investigated refrigerator with thermal energy storage. Numerical simulations using CFD software ANSYS Fluent were undertaken to characterize the airflow and temperature distribution in a natural convection thermal energy storage refrigerator. The model compared the household refrigerator temperature stability with different phase change materials (PCM) incorporated into the storage compartment. Scenarios investigated included the PCM orientation (vertical or horizontal), PCM temperature (use of water or eutectics) and compartment designs (conventional or drawer type appliance). From results they concluded that horizontal PCM configuration produces lower compartment temperatures than a vertical configuration. The temperature distribution with a horizontal PCM was tested experimentally and the results were in agreement with the CFD predictions. Both the simulation and the experimental results suggest that a eutectic with a phase change temperature below 0°C must be employed to maintain the compartment temperature within acceptable limits. [18]

Diaconu et al. (2010) analyzed a solar-assisted ejector cooling system with cold storage. Simulations were carried out over one year considering climatic data for a hot location (Béchar, Algeria) and the performance of the system was assessed for a set of design conditions. It was found that the simple control algorithm for the CSU considered by them can reduce cooling capacity of the AC system under certain conditions. On the other hand, some values of the CSM mass value can improve indoor comfort conditions (for the AH and CSU algorithms considered here) causing an apparent optimum value of CSM mass. [19]

6. Theoretical and Economic Analysis

Evodious Rutta (2022) has studied the deployment of solar-powered cold storage technologies. This study reveals that this technology is constrained by several factors, including low technology awareness, high investment costs, and low paying capacity among prospective users of SPCSTs. Despite these barriers, farmers interviewed were very positive about SPCSTs potential to prevent storage losses they experience regularly. [20]

Otanicar et al. (2012) have analyzed technical and economic comparison of existing solar cooling approaches, including both thermally and electrically driven. The results of the economic and environmental analysis of a variety of solar cooling schemes revealed some key details regarding system choice. For solar electric cooling the system cost is highly dependent on the system COP when PV prices remain at the current levels, but when prices are lowered the impact of COP becomes diminished. [21]

7. Conclusion

In conclusion, solar-powered cold storage with thermal energy storage backup has emerged as a promising technology for on-farm preservation of perishables. The use of renewable energy from the sun to power the refrigeration cycle, along with thermal energy storage backup systems, reduces energy consumption, increases cost-effectiveness, and improves the shelf-life of perishables. Various studies have been conducted on the design, fabrication, and testing of solar-powered cold storage systems. Economic analysis and feasibility studies have shown that the photovoltaic system with thermal energy storage is more effective in terms of ease of design, availability of technologies, higher NPV, and faster payback period. The paper has also identified some barriers to the widespread adoption of solar-powered cold storage systems, including high initial costs, lack of technical know-how, and inconsistent solar radiation. Overall, the technology has the potential to address the challenges of food preservation and storage, especially in off-grid and remote areas, and could contribute significantly to reducing post-harvest losses of perishable food items.

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