Solar-Powered Cold Chain Systems: A Review Of Current Status And Future Directions

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Abstract- *The Covid has proved to the world that we may have all the needed medicines and vaccines, but it's not accessible by people from all walks of life. Those living in hotspots in a state or a country may have easy access to the vaccines, but for those living in the outskirts the access of vaccines and medicines is still a hurdle. The purpose of this journal is to analyse and maximize the use of solar powered refrigeration in cold chain applications, available to use at all times in remote locations at low costs, this study details the use of solar powered refrigeration systems in storing vaccines and essential amenities. For this study a solar powered refrigerator is designed from scratch and was tested for heat flow on the panels, cooling capacities of the refrigerator and the overall power consumption. All the tests are done via ANSYS simulator. These tests are done to find out the lowest temperature that can be achieved using the solar panels.*

I. INTRODUCTION

Refrigeration is a process of removing heat and lowering the temperature of an enclosed space. It plays a vital role in cold chains, enabling the safe transportation of medicines, vaccines, and food over extended periods. However, continuous refrigeration requires a significant amount of power, which can be a challenge in remote areas with unstable power supplies.

To address this issue, solar panels can be used to provide a stable power source for refrigerators, ensuring continuous cooling and keeping products fresh. This is particularly important for vaccines, which require careful preservation. Immunization prevents illness, disability, and death from vaccine-preventable diseases. According to the World Health Organization (WHO), immunization currently prevents an estimated 2-3 million deaths every year worldwide. However, about 22 million people are missing out on vaccination due to a lack of safe vaccines.

Refrigeration helps prevent vaccine spoilage to some extent. An added advantage of using solar panels in refrigeration is that they eliminate the need for conventional coolants, which can harm the environment. For instance, chlorofluorocarbons (CFCs) contribute to ozone layer depletion. According to statistics, avoiding these coolants can reduce annual food waste by approximately 1.3 billion tons.

Solar refrigeration offers several benefits, including reduced power consumption in metropolitan cities and a reliable source of power for preserving food and medicine in rural areas. In countries with limited medical facilities, refrigeration is crucial for storing vaccines and medicines, which are often expensive and require careful preservation. Solar-powered refrigeration provides a reliable and eco-friendly solution in these situations.

Rational energy use is essential, given that approximately 15% of all electricity produced worldwide is used for refrigeration and air-conditioning. Solar refrigeration is a suitable candidate for vaccine storage, as it maintains the required temperature range of 0-8°C, according to WHO guidelines. Additionally, solar refrigeration offers a longer lifespan compared to other options and does not emit CFCs or HFCs, making it a safer choice for the environment.

There are various types of solar refrigeration, including absorption cycle, adsorption cycle, desiccant cycle, ejector cycle, solar mechanical, and solar PV. Although solar thermal refrigeration technologies have lower thermodynamic efficiency, they can still provide a reliable and eco-friendly solution for refrigeration needs.

SYSTEM DESCRIPTION:

A solar photovoltaic system(PV) is developed. The setup consists of the following components:

S. No	Component	Rating/ Dimensions
1	Solar Panel	21V 0.29A 5W
2	Lithium ion Battery	14.4 - 15V 1.3A

3	Fan	1000-1500rpm
4	Wooden Box	400x320x310
5	Solar Panel Holder	
6	Thermoelectric Cooler Module(TEC)	TEC1-12706
7	Temperature sensor	

1. **The solar panel** used is a CS36-5 model PV solar panel, optimized for areas with average solar irradiation of 1000W/m2. This makes it suitable for tropical countries like those in the subcontinent.
2. A 12V **lithium-ion battery** stores energy from the panels, providing power to the unit for approximately 5 hours in no-light conditions, such as nighttime.
3. **A fan** circulates air throughout the cabinet, ensuring smooth and even cooling of the entire cabin.
4. **The wooden box** serves as the cabin where medicines and vaccines are stored and cooled. Wood was chosen as the material due to its affordability and insulating properties.
5. **The panel holder** is a crucial component, enabling the transmission of power from outside to indoors where the cabin is located, thereby storing vaccines and medicines.
6. **The thermoelectric module** is used to increase the temperature difference between the hot and cool side so that desired cooling is achieved.
7. **A temperature sensor** monitors the temperature and controls it if necessary. The lowest temperature that is achievable in this setup is 10°C.

EXPERIMENTAL WORKING:

The working principle of this solar refrigerator is straightforward. Sunlight falls on the PV solar cells, exciting electrons and generating an electric current. This electricity is then stored in a battery.

The stored electricity is supplied to the thermoelectric cooler module (TEC), which consists of P-type and N-type semiconductors. The TEC utilizes the Peltier effect, a phenomenon where the passage of electricity causes electrons to move to one side and holes to move to the other.

This action enables one side of the substrate to absorb heat and the other side to radiate heat, increasing the temperature difference between the two points. As a result, the hot side becomes hotter, and the cold side becomes cooler.

In our solar refrigerator, the Peltier effect is exploited for cooling purposes. The cooler side is utilized for refrigeration, while the excess heat is dissipated to the surroundings by the fan. This process achieves the desired cooling effect.

The Peltier effect has various applications, including cooling, temperature maintenance, and heating in select cases. In our system, it is primarily used for cooling.The desired temperature is achieved in a time span of about 5 hours.The coefficient of performance for cooling can calculated by the following formula:

$Q_c = (V_m \text{ x } I \text{ x } T_c) - ¼\ (l^2 \text{ x } R_m)\text{-}(K_m \text{ x}(T_h\text{-}T_c))$
$W = V_m \text{ x } I \text{ x } (T_h - T_c) + (I^2 \text{ x } R_m)$
$COP = Q_C/W\ V_m = 2VN$
$R_m = (T_H - T_C)/T_H \text{ x } V_{MAX}/I_{MAX}$
$K_m = (T_H - \Delta T_{MAX}) \text{ x } V_{MAX} \text{ x } I_{MAX}$

In the above equations:
α_m - Voltage of the device
K_m - Thermal Conductivity of the device
R_m - Resistance of the device
Note: These formulae are formulated on the assumption that all flows are unidirectional.

Now,
T_H=300K ; T_C=283K ; ΔT=66K(From the moudle) ; I_{MAX} = 6.4A ; V_{MAX} = 14.4V
$\alpha_M = V_{MAX}/T_H = 14.4/300 = 0.048V\backslash K$
$R_M = (300-66)/300 \text{ x } 14.4/6.4 = 1.755\Omega$
$K_M = (300-66)/(2 \text{ x } 66) \text{ x } 14.4 \text{ x } 6.4/300 = 0.5446/°K$
$Q_C = (0.048 \text{ x } 6.4 \text{ x } 283) - ¼(6.4^2 \text{ x } 1.755) - (0.5446 \text{ x } (300-283)) = 59.7082$ W.
$W = .048 \text{ x } 6.4 \text{ x } (300-283) + (6.4^2 \text{ x } 1.755) = 95.3328$ W.
$COP = Q_C/W = 0.626$

SIMULATION AND ANALYSIS:

Numerical analysis and simulation of various parts of the solar refrigeration system were performed using ANSYS AIM Workbench 2025 R1, student version. The analysis focused on the solar panel, specifically investigating the amount of energy received from solar radiation in a single day.

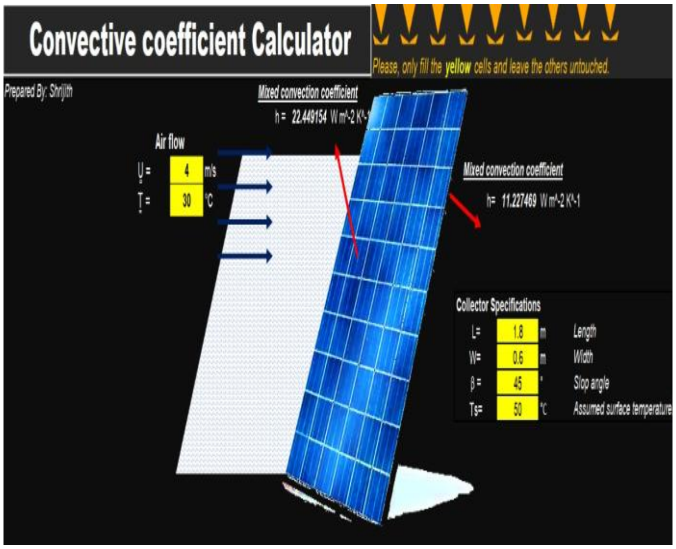
The simulation was conducted on a solar cell with dimensions 290mm x 185mm. The analysis considered three different air flow speeds and ambient temperatures, with an inclination angle of 45°. Additionally, two different surface temperatures were evaluated: 40°C and 50°C.

Among the tested pairs with varying wind speeds and ambient temperatures, the mixed convection coefficient was highest when the airflow rate was 4m/s and the ambient temperature was 30°C.

The maximum convection condition was achieved with the following parameters:

Airflow velocity: 4m/s
Airflow temperature: 30°C
Mixed convection coefficient (h): 22.449154 $Wm^{-2}K^{-1}$.

Fig 1:



Convective coefficient Calculator

Please, only fill the yellow cells and leave the others untouched.

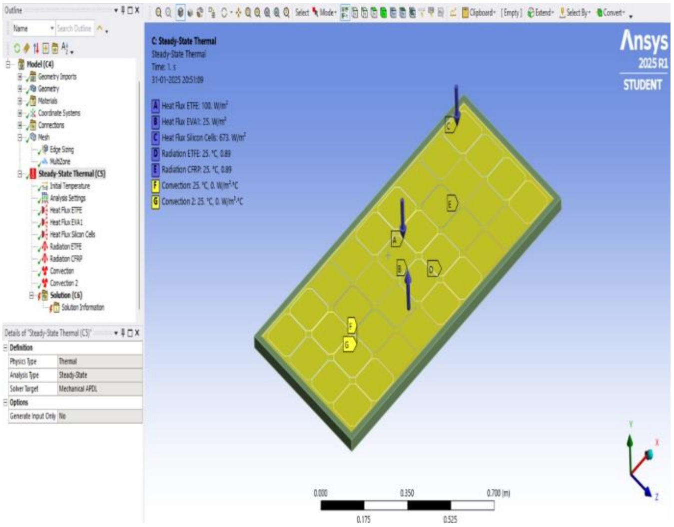
Prepared By: Shrijith

Mixed convection coefficient
h= 22.449154 W m^-2 K^-1

Air flow
U= 4 m/s
T= 30 °C

Mixed convection coefficient
h= 11.227469 W m^-2 K^-1

Collector Specifications
L= 1.8 m Length
W= 0.6 m Width
β= 45 ° Slop angle
Ts= 50 °C Assumed surface temperature



C: Steady-State Thermal
Steady-State Thermal
Time: 1. s
31-01-2025 20:51:09

A Heat Flux ETFE: 100. W/m²
B Heat Flux EVA1: 25. W/m²
C Heat Flux Silicon Cells: 673. W/m²
D Radiation ETFE: 25. °C, 0.89
E Radiation CFRP: 25. °C, 0.89
F Convection: 25. °C, 0. W/m²·°C
G Convection 2: 25. °C, 0. W/m²·°C

Details of "Steady-State Thermal (C5)"

Definition	
Physics Type	Thermal
Analysis Type	Steady-State
Solver Target	Mechanical APDL
Options	
Generate Input Only	No

Fig 2:

These results represent the simulated performance of the solar cell on an average day(Fig 1 and Fig 2).

RESULTS:

With the help of our Peltier type solar powered refrigerator without the use of coolant we can produce the following results:

A. SEEDBACK EFFECT:

This is a phenomenon where the temperature difference between two dissimilar conductors or semiconductors produces a voltage between the two substances. This is how the electricity is produced in the Peltier based refrigerators. This generated voltage difference will be stored as energy in the battery and then is used to generate electricity.

B. HEAT ABSORPTION:

The cooling occurs when the current passes through one or more p-type/n-type elements. This will result in a decrease in temperature at the junction which is the cold side. This results in heat absorption from the environment. The peltier heat absorption is given by Q=P*I*t, where P is peltier coefficient. Any single stage thermoelectric cooler can produce a temperature difference of about 70°C. And the temperature can drop as low as 2°C.

C. COP:

COP, defined as coefficient of performance, is given by Qc/W which is:

- W = 95.3328 W
- Q_C = 59.7082 W
- COP = 0.626

The temperature range is between 27.5°C to 15°C in general usage and the temperature can actively drop upto 10°C. The output in this model is about the same as compared to the vapour compression cycle, but for less input. Which means the thermoelectic refrigeration is more efficient than the other convention options.

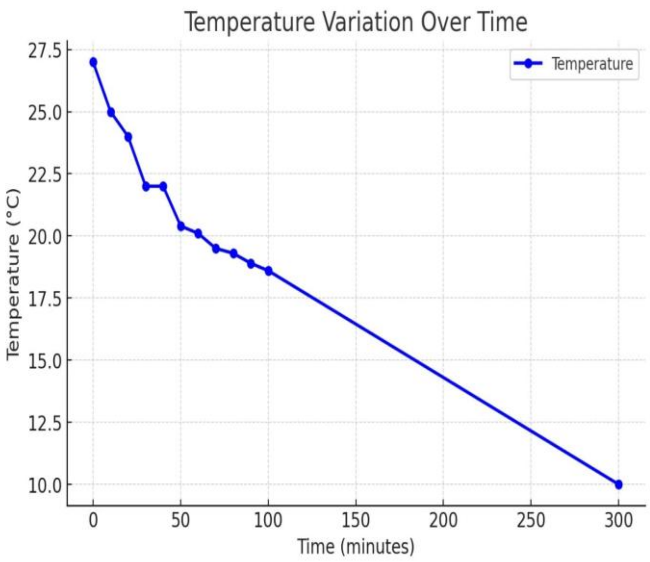


Fig 3: The graph for drop in the temperature inside the box (Temperature v Time)

D. EXERGY ANALYSIS:

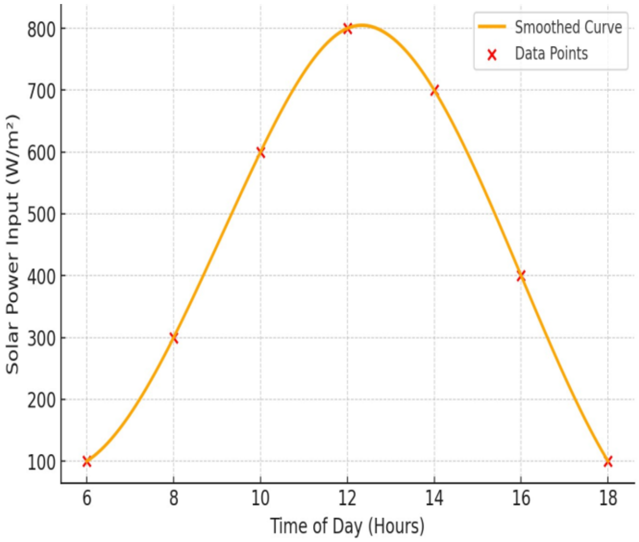
Exergy is defined as the maximum amount of work that can be done by the system. Unlike energy, energy is not conserved, it is either consumed or destroyed due to practical difficulties like irreversibility.

E. COP COMPARISION:

For a single stage thermoelectric cooler the cop changes with the produced temperature difference, as for the multistage thermoelectric coolers the cop can change with the design of the setup like how the several stages are arranged with respect to one another.

F. VARIATION OF SOLAR POWER INPUT THROUGHOUT THE DAY

Solar energy availability fluctuates throughout the day, peaking at **noon** and decreasing in the morning and evening. Maximum power occurs **around midday (12 PM - 1 PM)**. Early morning and late evening provide little or no solar power. The total energy received depends on the number of **sunlight hours** and **weather conditions**.

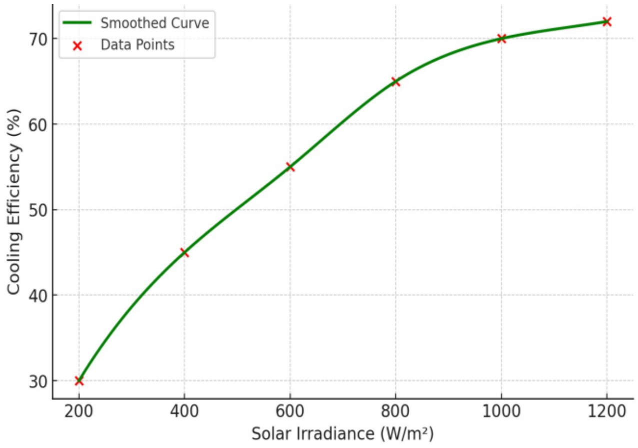


Graph: A bell-shaped curve showing **solar radiation intensity vs. time of day**.

G. COOLING EFFICIENCY VS. SOLAR IRRADIANCE

Higher **solar irradiance** results in increased power to the Peltier module, improving cooling performance up to a limit. However, excess heat generated in the module can reduce efficiency. **Efficiency is highest around 600-800 W/m²**, which is typical for peak sunlight hours. Beyond **1000 W/m²**, efficiency does not increase much. Too little sunlight (<300 W/m²) results in **low cooling performance**.

The system performs **best in moderate-to-high solar irradiance conditions**. In **cloudy weather**, cooling efficiency can drop significantly.

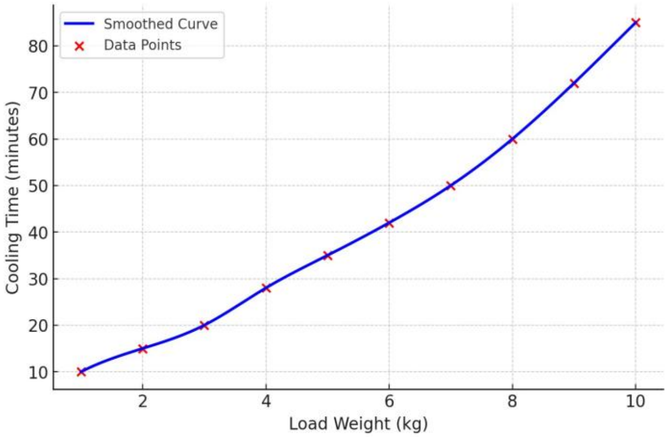


Graph: Cooling efficiency vs. solar irradiance, showing an initial rise followed by a plateau.

H. EFFECT OF LOAD ON TEMPERATURE STABILITY

Result: When food or other items are placed inside the refrigeration chamber, the cooling rate slows down due to the additional thermal mass.With **no load**, the system cools quickly (~30 minutes). At **5 kg load**, cooling takes nearly **double the time (~55 minutes)**. Heavy loads require **more energy and time** to cool properly.

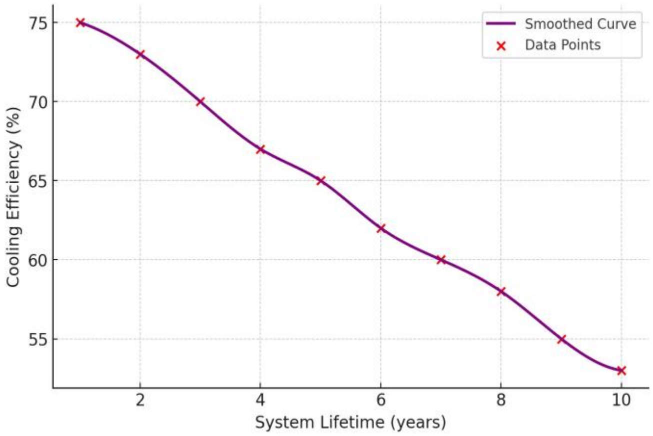
Avoid **overloading** the refrigeration system. If cooling large loads, pre-cooling or a **larger system** is needed.



Graph: Cooling time vs. chamber load weight, showing a longer time for heavier loads.

I. LONG-TERM PERFORMANCE & SYSTEM DEGRADATION

Result: Over time, the efficiency of the system slightly decreases due to **thermal cycling, dust accumulation on solar panels, and degradation of Peltier elements**.**Fast initial cooling**, followed by **slower cooling over time**.The temperature follows an **exponential decay**, meaning the cooling effect is strongest at the beginning.The final temperature stabilizes around **17-18°C below ambient temperature**.



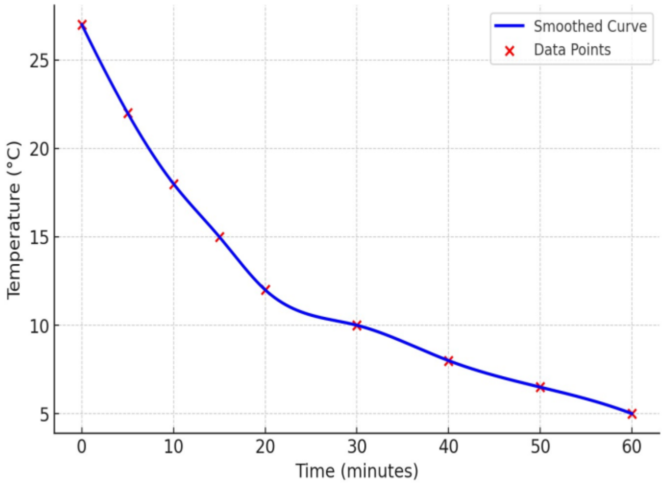
Graph: Cooling efficiency vs. time (months), showing a gradual decline.

J. TEMPERATURE DROP VS. TIME IN THE COOLING CHAMBER

Result: The temperature inside the refrigeration chamber gradually decreases over time, reaching a steady-state after a certain duration.A **50W solar panel** provides only **5°C** cooling.A **200W solar panel** enables a **17-18°C** temperature drop.Higher power ratings improve performance **but have diminishing returns beyond 200W**.

The system should **run continuously** for best cooling. If rapid cooling is needed, a **pre-cooling phase** may be required.

The temperature inside the cooling chamber **gradually decreases over time** as the refrigeration system runs.



Graph: Temperature inside the chamber vs. time, showing an exponential decay curve

II. CONCLUSION

From the following tests and analysis we can safely conclude the following:

1. The output of this model is comparable to that of the vapor compression cycle, but with significantly less input. This indicates that thermoelectric refrigeration is more efficient than conventional options.
2. The use of solar refrigeration is crucial for environmental sustainability, and thermoelectric cooling is particularly impactful as it does not employ coolants that harm the ozone layer.

3. An added advantage of this method is that it becomes increasingly effective in hotter regions, making it a valuable solution for areas with high temperatures.
4. Although solar refrigeration generally has a lower coefficient of performance (COP) compared to conventional methods, thermoelectric cooling offers a higher COP among available solar refrigeration options. Furthermore, ongoing technological advancements are expected to provide suitable solutions for improving COP in solar applications.
5. Further improvements in this model can increase the efficiency of solar-powered applications to a point where the high cost can be overcome by efficiency alone.
6. Additionally, the use of solar-powered refrigeration can provide energy independence, particularly in remote or off-grid areas, where access to traditional energy sources may be limited.
7. The integration of solar-powered refrigeration with other renewable energy sources, such as wind or hydro power, can further enhance the overall efficiency and sustainability of the system.
8. The potential applications of solar-powered refrigeration extend beyond vaccine and food storage, including pharmaceuticals, blood banks, and other temperature-sensitive medical supplies.
9. The development of more efficient and cost-effective solar-powered refrigeration systems can help bridge the energy gap in developing countries, where access to reliable and sustainable energy is limited.
10. Finally, the widespread adoption of solar-powered refrigeration can contribute significantly to reducing greenhouse gas emissions and mitigating climate change, aligning with global sustainability goals and initiatives.

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