Environmental friendly micro cold storage for last-mile Covid-19 vaccine logistics

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Abstract

Globally, vaccination plays a vital role in controlling the Covid-19 pandemic. However, the cold supply chain is essential for vaccine storage and logistics services. In a country like India, the last-mile logistics of vaccines is a challenging task. The cold chain is indispensable for the Covid-19 vaccine drive to the rural areas. The demand for cold storage increases rapidly due to the rapid Covid-19 vaccine drive. The conventional cold storage facility has a more significant threat to the grid power quality and environmental impacts. The energy demand and greenhouse gas emission of traditional cold storage lead to global warming. The micro cold storage facility has to be developed rapidly to accelerate the vaccine drive to the last mile of the county with reliable and affordable energy sources. In addition, climate change mitigation is ensured by the renewable energy utilization in the Covid-19 vaccine drive. The proposed novel micro cold storage aims to be silent, clean, mobile, without moving parts, and reliable for the last-mile vaccine logistics as a vaccine carrier to the remote rural areas. This paper deals with the novel design, development, and experimental investigation of solar photovoltaic powered thermoelectric-based micro cold storage as a Covid-19 vaccine carrier for rural areas. The design consideration of Covid-19 vaccine storage has been reported. The experimental results ensure the World Health Organization recommended vaccine storage (i.e., vaccine carrier) temperature range of +2 to +8 °C. Therefore, green energy and refrigeration system provide environmental sustainability by mitigating 700kg of annual carbon emission.

Keywords Covid-19 vaccine · Last-mile vaccine logistics · Micro cold storage · Solar photovoltaics · Climate change mitigation · Carbon emission reduction

Introduction

Globally, 37.1% of the world population has received the first dose of Covid-19 vaccination, and 23.7% are wholly vaccinated. In India, 31% of the people got their one dose of the Covid-19 vaccine, and 8.8% of the people are wholly vaccinated (Our World in Data 2021). The administration of Covid-19 vaccination is the only ultimate way to control the Covid-19 pandemic. The last-mile logistics delivery has to ensure correctly to accelerate the rate of vaccine administration. The last-mile vaccine logistics is a crucial process

because of its cold supply chain issues. In India, the last-mile vaccine delivery to remote rural areas is a challenging task. Despite 28,000 cold chain units in India, none can transport vaccines under −25 °C (Healthcare Global). Refrigeration for the cold chain plays an indispensable role in maintaining the property of the vaccine. The existing cold storage system has numerous friction-causing parts, and it is energy-intensive. It depends on traditional power sources with greenhouse gas emissions, the primary threat in reliable last-mile vaccine logistics in rural areas. Conventional refrigeration has global warming potential gases as a refrigerant, a more significant threat to the environment. The increase in cold storage facilities increases energy consumption and pollutes the environment through harmful refrigerant utilization (Saif and Elhedhli 2016). However, the thermoelectric-based solar-powered micro cold storage could solve the above discussed problem.

A thermoelectric component comprises two or more elements of N- and P-type-doped semiconductors. The

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internal construction of the thermoelectric module is configured electrically in series-connected and thermally parallel connected. A range of different shapes, substrate materials, metallization patterns, and module placement options are available. Cooling capacity is proportional to the degree of the input DC current and the hot side temperature of the thermoelectric module. Accurate temperature control of 0.1 °C is possible in the thermoelectric cooler. Heat flow regulation and surface temperature control are possible by changing the input current from zero to maximum. The hot side heat sink configuration ensures effective heat removal. No moving parts, zero circulating liquids (Hagenkamp et al. 2021), and zero hazardous gas emission are the significant advantage of a thermoelectric cooler compared to a vapor-compression refrigerator (Dimri et al. 2017). The solid-state, small form factor, any orientation, and zero gravity operation are the strength of the thermoelectric cooler (Cai et al. 2016).

The cold chain is inevitable for vaccine health (i.e.,) without any degradation in vaccine quality (Government of India Ministry of Health and Family Welfare 2016). The cold chain has been maintained from the manufacturing premises as a post-vaccine production process. The vaccine distribution is governed by the Government Regional Medical Store Depot (primary vaccine store) with the maintained temperature of +2 to +8 °C under walk-in cooler (WIC) and −15 to −25 °C kept under walk-in freezers. It is followed by state, district, and block vaccine store to the target public beneficiary through primary health center (PHC). The reefer vehicles are employed for vaccine logistics from the state vaccine store to the district vaccine store under the temperature range of +2 to +8 °C. In the district vaccine store, the temperature range of −15 to −25 °C is maintained through deep freezers (DF). The last cold chain point for the reefer vehicle is the primary health center. In the PHC, ice lined refrigerator (ILR) is employed for maintaining the temperature range of +2 to +8 °C. The overall cold chain is maintained from the manufacturing premises to the primary health center (Government of India Ministry of Health and Family Welfare 2016).

From the PHC to the vaccine beneficiary, the vaccine carriers have been utilized. Four ice pockets power the present vaccine carriers with a capacity of 1.7 l. The current vaccine carriers have various operational challenges. The challenges in the last-mile vaccine logistics are using non-electrical storage, limited capacity, and functional limitations like the health of ice pockets, transportation losses, exposure to sunlight, and chamber insulation. Therefore, the designed solar-powered micro cold storage enhances the vaccine drive of rural areas by overcoming the challenges in last-mile vaccine logistics and operational limitations of existing vaccine carriers.

The primary objective is to develop a solar-powered micro cold storage as a vaccine carrier for last-mile vaccine Covid-19 logistics. The proposed novel solar-powered micro cold storage enabled cold chain network has been shown in Fig. 1. The design, development, and experimental investigation have been carried out as per the World Health Organization (WHO) recommendations. The Covid-19 vaccines operational guidelines are released by the Ministry of Health and Family Welfare, Government of India (Government of India 2020) and are taken as gray literature. Table 1 gives the prescribed cold storage temperature by the government of India. Table 2 gives the World Health Organization (WHO) recommendation of the cold chain to be considered for vaccine storage and servicing (World Health Organization 2015) in district-level constraints.

Literature review

Reviews on challenges in last-mile logistics of Covid-19 vaccine

Globally, the last-mile logistics of Covid-19 is a difficult task. The effectiveness or success of the Covid-19 vaccine is determined in their last-mile delivery with the prescribed temperature condition (Lee and Chen 2021). The last-mile logistics of the mRNA-based Covid-19 vaccine required extremely cold temperature. The cold chain maintenance and storage of the Covid-19 vaccine have to be addressed appropriately (Gianfredi et al. 2021). Especially, Gam-Covid-19 vaccination can be stored at +2 to +8 °C (Ricco et al. 2021). Heat damage and freeze damage are the two significant challenges in the Covid-19 vaccine storage. A temperature above +8 °C could damage the vaccine quality. The result of heat damage is the permanent loss of potency, and it cannot be regained again (Government of India Ministry of Health and Family Welfare 2016). The temperature below +2 °C leads to freezing damage of vaccine. The mathematical model has been proposed for vaccine cold chain time delay between distributor and retailer. The distributors and retailers should maintain the appropriate cold chain to avoid vaccine degradation (Dai et al. 2021). In Norway, various coldtainers are investigated for their transportation cost and CO₂ emission. The various simulation and analysis studies concluded that a small box van (micro cold storage) has significant potential for CO₂ emission reduction (Sun et al. 2021).

In India, the 2.74 GW of cold storage electrical load during 2020 and cold storage is expected to grow up to 7.8 GW by 2030 (India 2016). Due to the Covid-19 pandemic, the surge in the increase of medical freezer is enormous in quality to regulate vaccine delivery. Vaccines with ultralow temperature requirements are estimated to have a 35 times higher environmental impact than the conventional medical

Fig. 1 Proposed solar-powered micro cold storage in the vaccine cold chain network

Table 1 The Covid-19 vaccine cold storage temperature requirements

S. No.	Vaccine	Required temperature
1	Covishield by the University of Oxford, UK/ AstraZeneca	+2 to +8 °C (Government of India 2020)
2	Covaxin by Bharath Biotech, India	+2 to +8 °C (Bharatbiotech 2020)
3	Sputnik V by Gamaleya National Center, Russia	+2 to +8 °C (SPUTNIK V 2021)

Table 2 Recommended vaccine storage temperature by the World Health Organization (World Health Organization 2015)

S. No	Object	Temperature	Effect
1	Vaccine (liquid)	+2 °C	Lower threshold temperature to avoid freezing
2	Vaccine (liquid)	+ 8 °C	Higher threshold temperature to avoid the risk of microbial growth
3	Vaccine (diluent)	+2 °C	Diluent should never be frozen
4	Vaccine (diluent)	+ 8 °C	Higher threshold temperature
5	Vaccine (lyophile)	+2 °C	Lower threshold temperature to avoid freezing
6	Vaccine (lyophile)	+ 8 °C	Higher threshold temperature of lyophile

freezer (Jiang et al. 2021). In India, the cold storage for a vaccine under refrigerated temperature is minimal due to its tropical climatic conditions (Healthcare Global). Apart from the ramping up of cold chain storage units in India, it is necessary to enhance the advanced technology of IoT and blockchain to avoid counterfeiting and ensure last-mile delivery (Hindu). Due to the increase in the Covid-19 pandemic, the conventional last-mile delivery process became more expensive and time-consuming (Srivatsa Srinivas and Marathe 2021). In India, the primary bottleneck in Covid-19 vaccine distribution is due to the vaccine cold storage and refrigerated transportation (Kumar et al. 2021). Therefore, the micro cold storage could address the issues on last-mile vaccine delivery.

Reviews on cold storage and its environmental impact

The cold storage facilities are contributing carbon emissions directly and indirectly to the environment. The conventional cold storage facilities are powered by entirely (or) partially halogenated refrigerants and electrical energy. The halogenated refrigerants are significantly derived from hydrocarbons and directly pollute the environment. Electrical energy utilization is an indirect form of carbon emission to the environment (Benhadid-Dib and Benzaoui 2012; Nadimuthu et al. 2021b).

In the refrigeration industry, the ozone depletion potential (ODP) and global warming potential (GWP) are significant in R22 refrigerant (Shaik and Babu 2019). The utilization of alternative or natural refrigerants could reduce the environmental impact for sustainability (Padmavathy et al. 2021). The total equivalent warming impact (TEWI) index was calculated for obtaining the alternative to R22 for its anthropogenic environmental issues. Based on the TEWI index, the performance, toxicity, and flammability of various R22 alternatives are studied, and the results revealed that the R1270, RM30, and RM50 are considered as environmentally friendly alternatives to R22 (Shaik et al. 2020). In addition, the weather parameters (CO₂ emissions, temperature, and humidity) and climate change significantly increase the COVID-19 infections (Sarwar et al. 2021). From the review, to overcome the anthropogenic effect, a solid-state thermoelectric cooler without any refrigerant is highly appropriate for environmental sustainability with the desired temperature range.

Reviews on the design of solar photovoltaics

India requires the development of sustainable cold storage. The penetration of renewable energy resources ensures sustainability in the operation of cold storage (Team). The solar photovoltaic-based vapor compression

refrigeration system is employed in district-level cold storage requirements (Government of India Ministry of Health and Family Welfare 2016). The vapor compression refrigeration system emits greenhouse gas emissions during its operation. Therefore, an environment-friendly cooling system is essential for sustainability. The CO₂ emission can be reduced drastically by the intervention of renewable energy resources and forest area (Marimuthu and Kirubakaran 2013; Waheed et al. 2018). The design of a solar integrated vapor absorption refrigeration system is developed for the tropical agro-produce storage in the rural areas (Selvaraj and Victor 2021a; Selvaraj et al. 2021). The software-based design of a solar photovoltaic power plant is carried out for energy conservation and carbon emission reduction (Lalith Pankaj Raj and Kirubakaran 2021; Nadimuthu et al. 2021a). The systematic design of the solar photovoltaic system is carried out for the process industry and reported for energy and carbon emission reduction (Nadimuthu and Victor 2021a). Solar power generation is dependent on the operating temperature of the solar photovoltaic module (Lalith et al. 2018). The various design considerations like operating module temperature, seasonal variation, shadow, and performance of the solar photovoltaic system are discussed for better design of the system (S. Chopade et al. 2018). Solar photovoltaics are highly suitable for their stand-alone operation (Nadimuthu and Victor 2021b). The life span of 25 years is assured to solar photovoltaics (Lalith Pankaj Nadimuthu Raj et al. 2019). Clean, solid-state, reliable, and maintenance-free energy are the advantages of solar photovoltaics (Vigneshwari et al. 2016).

Reviews on the design of thermoelectric cooler

The design of a solar-powered thermoelectric cooler should possess the qualities for the storage of the Covid-19 vaccine. The optimal selection of materials for the module should match the design requirement and the properties of materials (Segarra et al. 2015). The material should possess the following criteria like chemically, thermally, and structurally strong for durability and environmental safety. Structural stability must accommodate vibrations and thermal cycles with no significant degradation in the life span of about 5 to 10 years at the industrial operating condition cost-effectively (Segarra et al. 2015). The heat transfer loss is due to improper insulation distribution, leading to energy loss (Sevindir et al. 2017). The cryogenic transport box was constructed using composite nanomaterial and vacuum insulation plate. The multiwall carbon nanotube's thermal conductivity is about 0.9021 W/(m.K), accounting for a 19.17% increase in insulation capacity (Xu et al. 2018). The stack density determines the quality of the cooling inside the chamber (Wang et al. 2019). The higher the cold air velocity inside the cold chamber, the larger the cold chamber's

temperature reduction. The best cooling performance is achieved at the cold side air velocity of 5 m/s (Wang et al. 2019). The material of the thermoelectric module, position of the thermoelectric module, insulation of thermoelectric chamber, and cold air velocity of the chamber are the critical parameters to obtain better cooling. Therefore, the thermoelectric cooler is best suitable for the stand-alone operation of last-mile vaccine logistics in rural areas.

From the review, the last-mile logistics of the Covid-19 vaccine is a challenging task for its operational temperature conditions. The novel thermoelectric-based micro cold storage has a significant breakthrough in the last-mile vaccine logistics. The renewable energy penetration in the stand-alone micro cold storage could reduce the greenhouse gases and lead to climate change mitigation. Therefore, the development of solar photovoltaic-based micro cold storage could enable the last-mile logistics of the Covid-19 vaccine to a greater extent.

Design consideration of micro cold storage of Covid-19 vaccine

Selection of module

The choice of thermoelectric material is a critical stage of designing the system. The materials should possess high Seebeck coefficient and electrical conductivity with low thermal conductivity for the high figure of merit (ZT) and power factor (Segarra et al. 2015). The chosen materials should be free from harmful content with low-cost materials like Al, Fe, and Si with environmental consideration. The module should be capable of producing the recommended vaccine storage temperature range.

Positioning of module

The positioning of the module plays a significant role in the performance of the thermoelectric cooler. The cold chamber wall-mounted thermoelectric modules substantially reduce chamber temperature (Mirmanto et al. 2019). Therefore, positioning thermoelectric modules in the cooler significantly impacts the chamber temperature reduction of vaccine storage micro cold storage.

Insulation of the cold chamber

The insulation materials, which exhibit low thermal conductivity, high structural strength, and high-water repellent properties, are lightweight, odorless, nonflammable, and low-cost which are the best-suited properties for insulating the cold chamber. Good insulation reduces the operation and maintenance cost by reducing the thermal leakage from the

chiller and reducing the system's power consumption. For the best distribution of insulation in a cold chamber, it is essential to include the variation of temperature differences (i.e., change in temperature). In the vaccine storage chamber, a proper rubber gasket is necessary for controlling the thermal leakage from the cold chamber to the hot surface and vice versa.

The porosity of the stack

The porosity of the input stack is an essential parameter in the design of the cold chamber. The cooling rate in the cold chamber is based on the porosity of the input stack. When the porosity increases, the stack's flow resistance increases, so the cold air velocity is impaired heavily and resulting in a low cooling rate. Therefore, while designing a cold chamber, it is preferred to load the chamber with less porosity to have a better convective heat transfer (Wang et al. 2019). Also, the cooling bed porosity has better pressure and temperature drop in the cold chamber (Ngcobo et al. 2012). Improper (or) unorganized storage of Covid-19 vaccine vial inside the chamber leads to vaccine freeze or heat damage (Government of India Ministry of Health and Family Welfare 2016). The stack density is directly proportional to the vaccine quality. Therefore, optimal loading of 75% inside the chamber is best suitable for Covid-19 vaccine storage in the solar-powered micro cold storage.

Cold air velocity inside the cold chamber

The cold chamber inner fan velocity plays a vital in the performance. For the porous media particle (i.e., Reynolds number ($Re_p < 1$)), the airflow rate is proportional to Darcy law's pressure drop. Darcy law is the first law provides the linear relationship among the pressure drops ∇p (Pa/m) vs. volume arranged (Zhao et al. 2016). It is essential to maintain the air velocity inside the cold chamber for better performance. The optimal temperature should be maintained for quality Covid-19 vaccine delivery.

Methodology

The design, development, and experimental investigation of solar photovoltaic-based micro cold storage are initiated by designing a thermoelectric cooler. The design and development of solar photovoltaic power source and experimental analysis have been proposed on the solar-powered thermoelectric cooler. The systematic theoretical design of thermoelectric cooler is carried out by considering the international standards for the last-mile logistics of the Covid-19 vaccine. From Tables 1 and 2, it is concluded that the maximum and minimum temperature recommendations for Covid-19

vaccine logistics and service. Therefore, the lowest required temperature inside the cold chamber is about +2 °C with +/– 1 °C as a buffer for the cooler's optimal operation. In addition, the design consideration for the Covid-19 vaccine storage in the solar-powered thermoelectric cooler (micro cold storage) is considered and reported as follows.

Design of solar-powered micro cold storage

The design considerations of solar photovoltaics based micro cold storage of Covid-19 vaccine:

1. The required temperature range of +2 to +8 °C is essential for solar-powered micro cold storage of the Covid-19 vaccine.
2. The direct and battery-driven are the two modes of stand-alone micro cold storage operation.
3. The optimal tilt angle and shade-free mounting are essential for the maximum solar power generation to achieve direct-driven mode.
4. The 6 h of battery autonomy is chosen for last-mile vaccine logistics.
5. The depth of discharge (DOD) of 30% is chosen for battery selection.
6. Five hours of sunshine is considered for solar photovoltaic module selection.
7. The overall solar module derating factor of 15% is considered, including 5% for operating temperature, 3% for dust, 2% for cabling losses, and 5% for others.

Design of micro cold storage system

Estimation of heat loads

The heat loads of the thermoelectric system are mainly classified into active and passive loads. The active load is a dynamically heat-producing load. The passive loads are parasitic by the heat transfer of radiation, conduction, and convection. Generally, the active and parasitic passive loads are calculated for the better and optimized design of the thermoelectric cooler (Marlow Industries).

Estimation of radiation heat load

The proximity of two different temperatures induces heat transfer between them. According to the thermodynamic laws, heat transfer takes place from the high temperature to the low-temperature level. Therefore, the hot body faces net heat loss, and the cold body gains heat.

$$Q_{\text{radiation}} = F e s A \left((T_{\text{amb}})^4 - (T_C)^4 \right) \quad (1)$$

where

$Q_{\text{radiation}}$	passive radiation loss (W)
F	shape factor (worst-case scenario = 1)
e	emissivity (worst-case scenario = 1)
s	Boltzmann constant ($5.667 \times 10^{-8} \text{ W/m}^2 \text{ K}^4$)
A	area of the chamber (m^2)
T_{ambient}	ambient temperature (K)
T_C	cold chamber temperature (K)

Estimation of convection heat load

The amount of heat transfer is purely dependent on the amount of flow rate.

$$Q_{\text{Conv}} = h A (T_{\text{air}} - T_C) \quad (2)$$

where

$Q_{\text{Convective}}$	convective heat load (W)
h	convective heat transfer coefficient (air at 1 atm = $21.7 \text{ W/m}^2 \text{ }^\circ\text{C}$)
T_{air}	air temperature ($^\circ\text{C}$)
T_C	cold temperature ($^\circ\text{C}$)

Estimation of conduction heat load

The conductive heat transfer occurs only when there is a direct interaction of molecules. This molecular heat transfer occurs from the high-temperature to the low-temperature zone.

$$Q_{\text{Cond}} = \frac{k A \Delta T}{L} \quad (3)$$

where

$Q_{\text{conduction}}$	conductive heat load (W)
k	thermal conductivity ($\text{W/m } ^\circ\text{C}$)
L	heat path length (m)
ΔT	temperature difference ($^\circ\text{C}$)

Overall heat load of cooler

By considering the cold chamber's 12L capacity is made of Styrofoam insulation medium with a dimension of $0.41 \text{ m} \times 0.21 \text{ m} \times 0.21 \text{ m}$. The micro cold storage of the covid-19 vaccine is equipped with the thermoelectric cooling module for remote rural areas. Therefore, based on Eq. (1), the radiation passive load is calculated as 0.000077 W . The passive convective load of 2.97 W is calculated using Eq. (2). The passive conduction load 0.00144 W is calculated using Eq. (3), and active load is estimated as the system's input power 55 W . Therefore, the overall heat load of the system is considered as $57.97\text{--}60 \text{ W}$.

Defining the temperature, number of stages, and selection of TE module for Covid-19 vaccine storage

From the literature review, +2 to +8 °C of temperature requirement is essential for the Covid-19 vaccine storage. The cold side temperature of +2 °C and the maximum change in temperature of 35°C to 40°C are suitable for Covid-19 vaccine storage. According to the design consideration, the single-stage TEC is sufficient to change temperature (ΔT) up to 64 °C. Therefore, single-stage TEC is chosen for Covid-19 vaccine storage. The thermoelectric module has been made up of Bi₂Te₃ (bismuth telluride) with a rated DC input voltage of 12V and an input current of 4.6 A. The DC power rating of the module is 55 W.

The cooling capacity (Q_C) is the amount of actual work done, and the coefficient of performance (COP) measures the efficiency of the system. Equations (4) and (5) are used for obtaining the cooling capacity (Q_C) and COP, respectively.

$$Q_C = (m C_p \Delta T) / \Delta t \quad (4)$$

$$COP = \frac{Q_C}{P_{in}} \quad (5)$$

where

m mass (kg)
 C_p specific heat capacity (J kg⁻¹ K⁻¹)
 Δt change in time (Second)

Design of solar photovoltaic power system

From the design consideration, a total energy requirement of 400 Wh is required for 6 h of the micro cold storage operation. The energy requirement of 570 Wh is required by considering the depth of discharge of the battery. The system voltage of the 12V DC supply is chosen. Equation (6) is used to obtain the solar photovoltaic module wattage (Selvaraj and Victor 2021b).

The solar photovoltaic module sizing is carried out by considering the 5 h of sunshine

$$\text{Solar Module Sizing, } W = \frac{\text{Total Energy Required}}{(\text{Sunshine Hours} * \text{Module Efficiency})} \quad (6)$$

$$\text{Solar Module Rating, } W = \frac{400}{(5 * 0.85)} = 94.12 \text{ W} \quad (7)$$

Therefore, the higher rating of 100 WP polycrystalline solar photovoltaic module is chosen for the micro cold storage. The technical specification of the polycrystalline module is as follows: open-circuit voltage (V_{OC}) of 21.5 V, short circuit current (I_{SC}) of 6.2 Ampere, maximum voltage, (V_{max}) of 17 V, maximum current, (I_{max}) of 5.88 Ampere.

Equation (8) is used to calculate the battery capacity. The battery bank capacity determined by considering the depth of discharge of 30% and the system voltage of 12V,

$$\text{Battery Capacity, Ah} = \left(\frac{\text{Total Energy}}{(\text{Depth of Discharge} * \text{System Voltage})} \right) * 100\% \quad (8)$$

$$\text{Battery Capacity, Ah} = \left(\frac{400}{(70 * 12)} \right) * 100\% = 47.62 \text{ Ah} \quad (9)$$

Therefore, the higher rating of 50-Ah lead-acid battery is chosen for the micro cold storage. For the effective charging of 50 Ah lead-acid battery within 5 h of sunshine, 10% of battery capacity determines the charging current of the battery. The charging current of 5A is sufficient for charging the battery. Therefore, a PWM-based solar charge controller of 12V/8A is selected for effective battery charging.

The design of solar-powered micro cold storage of Covid-19 vaccine is as follows: a 55-W thermoelectric cooler, 100-W_p polycrystalline solar photovoltaic module, 12V/8A PWM-based solar charge controller, 12V/50 Ah lead-acid battery for 6 h of operation.

Experimental analysis on solar photovoltaic-powered thermoelectric cooler

Based on the design calculation, the experimental setup is developed in the laboratory for micro cold storage performance analysis and shown in Fig. 2. The thermoelectric module is a solid-state device made up of Bi₂Te₃ (bismuth telluride). It has the potential to operate at any irregular operating condition with the proper Styrofoam insulated container for the dynamic operating condition (i.e., vaccine carrier). The setup can operate under both the direct solar photovoltaic power and DC power stored in the battery. The K-type thermocouple is used for temperature measurement and data logging purposes. The 1-min once sample integration time interval is preset in the data logging operation. The setup has been equipped to conduct the performance characterization of solar photovoltaic integrated micro cold storage, as shown in Fig. 2.

The experimental system is integrated with the 100 W_p solar photovoltaic module through the pulse width modulation-based 12V/8A charge controller. The experimental analysis is carried out in the latitude of 10.27° N and longitude of 77.94°E. The tilt angle of 11° from the ground is chosen for the better mounting of the solar photovoltaic module. A 50-Ah lead-acid battery is integrated with the system for the stable operation. An aluminum-based heat sink is equipped in the hot side of the Peltier element. The overall dimension of the heat sink is 100 × 100 × 20 mm. The heat sink is configured with 20 number of 5-mm-thick

Fig. 2 Experimental setup of solar-powered micro cold storage for Covid-19 vaccine

aluminum fins for effective heat transfer. In addition, the 3-W rated forced cooling fan is fixed over the heat sink for simulating the dynamic property of the vaccine carrier (convective mode of heat transfer).

Results and discussions

The current-voltage characteristics curve of the solar photovoltaic system is graphically illustrated in Fig. 3. Solar light energy is converted into direct current electrical power output. The maximum power point is achieved by considering the operating conditions of the thermoelectric cooler. The pulse width modulation (PWM)–based solar charge controller effectively obtains the maximum power point (MPP). The power versus voltage characteristics curve illustrated

the total solar power generation and to obtain the maximum power point operation for supplying DC power supply to the micro cold storage and shown in Fig. 4.

The input electrical power characteristics of solar-powered micro cold storage are illustrated in Fig. 5. The operating current versus voltage characteristics curve indicates the input operating power of solar-powered thermoelectric-based micro cold storage. The linear curve fitting technique is adopted for achieving a 95% confidence bound. As the DC input voltage increases, the net DC power input will also increase and vice versa. Therefore, maximum cooling capacity (QC) and COP are achieved during the optimal voltage and current input to the system.

The chamber temperature of the solar-powered micro cold storage is illustrated in Fig. 6. Based on the experimental analysis, the temperature is dropped from +24 to +8 °C with a time taken of 35 minutes. Further, +8 to +3.3 °C temperature is achieved within the time of 25 min. One-hour time period is required for attaining the +3.3 °C. Therefore, within 30 min of operation, micro cold storage can attain the required vaccine storage temperature range.

Based on the Peltier effect, the sum of current flow is directly proportional to the cooling capacity. From the experimental analysis, the cooling capacity and coefficient of performance are calculated. At the maximum change in temperature region, the minimum cooling capacity and coefficient of performance are achieved. In the minimum change in temperature, the maximum cooling capacity and coefficient of performance are achieved. Therefore, the optimal values are essential for the better performance of the system. In the optimal change in temperature (ΔT) of +17 °C, maximum COP of 0.2131, and cooling capacity of 11.22 W is achieved. In the dynamic environment, the speed of the vehicle is a positive indicator for effective heat removal. In addition, turning ON of micro cold storage (i.e., vaccine

Fig. 3 Current versus voltage characteristics of solar photovoltaics

Fig. 4 Power versus voltage characteristics of solar photo-voltaics

Fig. 5 Micro cold storage operating current versus operating voltage

Fig. 6 Chamber temperature of solar-powered micro cold storage

carrier) before the service (operation) is essential for attaining the recommended Covid-19 vaccine storage temperature inside the cold chamber to avoid operational hindrance.

Solar-powered micro cold storage for climate change mitigation

Conventional refrigerators are energy-intensive and directly/indirectly generate carbon emissions. According to the Bureau of Energy Efficiency (BEE), India, the energy consumption of a 210-l vapor compression refrigerator is 346 kWh per annum (Retailer Training N, Programme 2021). According to the Central Electricity Authority (CEA) of India, CO₂ emission of 2kg per kWh of electricity utilization (GOI-MOP 2018). The annual carbon emission potential of 692–700 kg is obtained by comparing solar-powered micro cold storage with the single vapor compression refrigeration system. Therefore, the paradigm shift towards the thermoelectric-based solar-powered micro cold storage could address the carbon emission issue sustainably.

Discussion and limitation of solar-powered micro cold storage

The solar-powered micro cold storage is intended to achieve the last-mile vaccine logistics of rural areas. The discussion commences with the novel design and development of solar-powered micro cold storage as per the WHO recommendations and manufacturer prescribed Covid-19 vaccine storage temperature. The experimental investigation is carried out for the solar-powered micro cold storage in outdoor laboratory conditions. The operating hours, solar charge controller-PWM, and fast-charging feature are the limitations of the developed solar-powered micro cold storage. Therefore, the system with maximum power point tracking (MPPT) controller for the time-varying solar radiation and fast-charging features for operational convenience have to be addressed in future work. Also, the Internet of Things (IoT) intervention could enable effective last-mile vaccine logistics to rural areas.

Conclusion

The last-mile vaccine logistics is a challenging task, particularly for Covid-19 vaccines. Solar-powered micro cold storage development clearly paves the way for last-mile vaccine delivery without any vaccine degradation. In this paper, solar power micro cold storage was designed and analyzed for Covid-19 vaccine storage. The Covid-19 vaccine storage studies were carried out by the gray literature prescribed

by the WHO and factsheets of vaccine manufacturers. The results have shown the feasibility for the intervention of solar-powered micro cold storage as a vaccine carrier to the last mile of the vaccine logistics. The key findings are:

1. Climate change mitigation is ensured by the intervention of renewable energy resources (solar photovoltaics) and refrigerant-free micro cold storage (thermoelectric cooler) in the vaccine cold chain network.
2. Solar-powered micro cold storage ensures sustainability by mitigating 700 kg of annual carbon emission.
3. The 12-l capacity of solar power micro cold storage is obtaining the lowest temperature of +3.3 °C.
4. The prescribed operating temperature of +2 to +8 °C is achieved for vaccine storage.
5. The 100 W_p polycrystalline solar photovoltaic module with a 12V/50 Ah battery is sufficient for 6 h of stand-alone operation.
6. The stand-alone operation of the solar-powered micro cold storage ensures environment-friendly last-mile vaccine logistics.
7. The global vaccination drive will accelerate drastically in the remote/rural areas for controlling the Covid-19 pandemic.

The solar-powered micro cold storage facilitates as a green vaccine carrier for the environmentally sustainable last-mile vaccine logistics. The intervention of solar photovoltaics is ensuring sustainability through zero greenhouse gas (i.e., zero harmful refrigerant to the environment) in the last-mile vaccine delivery. The last-mile vaccine logistics through the solar-powered micro cold storage is highly feasible in rural areas.

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Availability of data and materials The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Author contribution All authors contributed to the study, conception, and design. Material preparation, data collection, and analysis were performed by Lalith Pankaj Raj Nadimuthu. Kirubakaran Victor wrote the first draft of the manuscript and all authors commented on the previous version of the manuscript. All authors read and approved the final manuscript.

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Declarations

Ethical approval This paper does not contain any studies with human participants or animals performed by any of the authors.

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Consent for publication Authors transfer to Springer the publication rights and warrant that our contribution is original.

Competing interests The authors declare no competing interests.

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