Mathematical modelling and sizing of solar photovoltaic-powered decentralised cold room with hybrid storage system

Sreelekha Arun[1*], Anindita Roy [1*], Stefano Landini [2], Akshay Pahade[3]
[1]Symbiosis Institute of Technology, Pune, India
[2]University of East Anglia, Norwich, UK
[3]Gratitude Synergy, Pune, India
*Corresponding authors: sreelekha.phd2022@sitpune.edu.in, anindita.roy@sitpune.edu.in

Highlights

- Development of mathematical model for decentralized cold room with hybrid energy storage.
- Methodology to find the minimum battery capacity corresponding to known compressor and solar PV rating.
- Generation of design space to obtain set of feasible options for the system parameters.
- Optimum configuration identified based on minimum Cost of Energy (CoE).

Abstract

Cold-chain management plays a crucial role in the agriculture sector. However, traditional centralized cold storage facilities often fail to meet the needs of rural and remote areas due to high logistics costs, inadequate infrastructure, and power supply challenges. Hence, decentralized cold rooms are essential for enhancing food security, reducing post-harvest losses, and supporting small-scale farmers and businesses. Standalone cold storage systems preserve harvest at farm-gates, especially in rural areas with disrupted electric supply. This study proposes to develop a mathematical model for cold storage, working on vapour compression refrigeration system, using solar power with battery and thermal (hybrid) energy storage, making it a grid-independent, stand-alone unit. The developed model is simulated over a given time horizon for a specified set of weather conditions, to obtain a set of feasible options for the system parameters. A design space, which is a collection of all such feasible options, is generated on the plot of solar photovoltaic rating vs battery capacity for varying compressor power for a minimum of 6 hours of thermal backup. System optimisation is undertaken by minimising the Cost of Energy (*CoE*) to arrive at the optimum solution from these feasible options. For illustration, a 3.4m^3 cold room operation on a typical day in April was simulated. The optimum combination comprised of 0.9 kW compressor power, 13.3 kW of solar PV rating and 4.54 kWh of battery capacity, for which CoE was evaluated as 8.57 Rs/kWh. Experimental results highlighted a reduction of 38% in the energy consumption with PCM integration in a decentralised cold room.This methodology is generic and can be flexibly adopted for cold room of varying storage capacity, proving to be advantageous for future scalability.

Keywords: Decentralised cold room, hybrid storage, design space, mathematical modelling, system optimization

Introduction

Increasing globalisation of food supply chain coupled with intensification of weather changes emphasises the need to develop an effective and economically viable cold chain solution [1]. The agriculture landscape of tropical countries like India is witnessing a major shift from grain-based agriculture to more high-value sectors such as horticulture, livestock and dairy [2]. India's position as the world's second-largest fruit and vegetable producer, makes it increasingly imperative to prioritise the development of its cold chain industry. This will ensure even product distribution and market price stabilisation from production centres to consumption centres [3]. Cold storage technology forms an integral part of this cold chain management that is essential in preserving the nutritional quality of these perishable products and maintaining their optimum freshness [4]. Development of these facilities, especially if set near the farms, provides easy accessibility to farmers, in addition to playing a crucial role in the reduction of post-harvest losses [5], [6]. Figure 1 displays the sector wise post-harvest food losses according to the Ministry of Food Processing Industries, Government of India, highlighing the need to focus on the fruits and vegetables sectors [7]. It may be noted that the cold storage facilities are highly energy dependent and are primarily operated on fossil fuel-based electricity [5]. Powering remotely located on-farm cold storages poses a major challenge due to inadequate grid connectivity, causing critical operational issues like reduced voltage, power fluctuations, frequent power cuts and long-duration breakdowns during storms, rainfall, etc. [8]. This is a major bottleneck that has hindered the development of cold storage and cold chain facilities in rural India [9].

An effective strategy to minimise these issues is the use of renewable energy to run the cold rooms [10]. Off-grid systems have the potential to minimise the vulnerability put forth by the conventional on-grid energy systems [11]. Solar energy, especially, is widely available and offers good opportunities in India due to its tropical location, leading to fossil fuel usage reduction [12], [13]. However, the intermittency of its availability is the point of concern, which can be overcome by incorporating thermal energy storage [12], [14]–[17]. Thermal batteries using phase change materials (PCM) are gaining popularity due to their ability to decouple production and demand of energy [18] and also provide eco-friendly solutions to minimise active power consumption [19]. Its advantages include low operational and energy costs, maintenance of the desired temperature and humidity of the product stored, and improved compressor life due to longer off-time period [20]. While the thermal storage will provide backup and moderate the thermal fluctuations, the electric

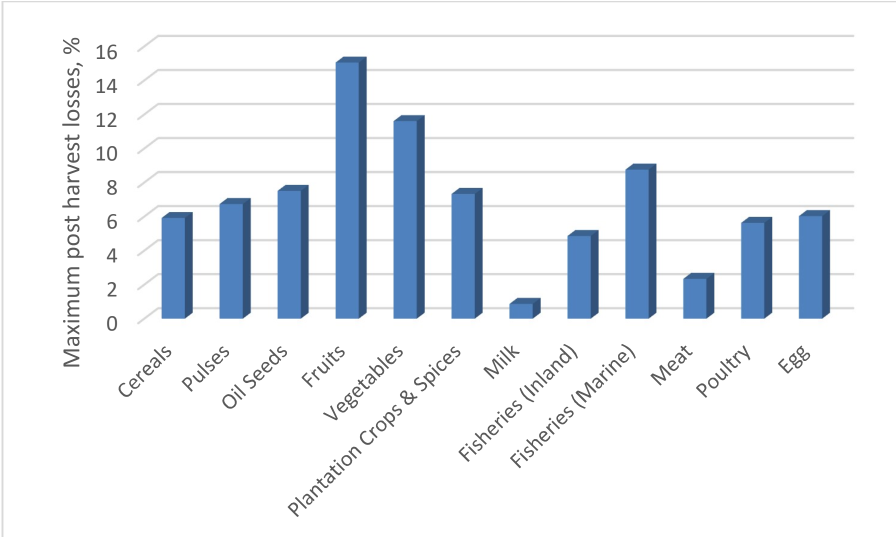

Figure 1: Sectorwise post harvest food losses in India [7]

storage plays a significant role during the non-sunshine hours and helps in levelling the mismatch between supply and demand of power [21], [22]. Batteries store the excess energy produced during the sunshine hours and make it available when the sun's energy cannot be directly utilised. Electrical battery is a reliable solution due to its flexibility in directly meeting the electrical load that the consumer is billed for [23]. However, though the cost of batteries is declining, their incorporation into cold storage units is still an underexplored area of research. While many researchers have attempted to develop the optimisation technique for a single storage type, there is no standard method to guide the system designer in the process of selecting or sizing a cold room system with a hybrid combination of thermal and electrical storage [23]. Also, variability in the cooling technologies available makes it important to select the appropriate method for the integration of a hybrid storage system that would result in cost effectiveness. Different cooling methods are being adopted for running the cold storages in India, as enlisted in Table 1, stating their initial cost along with merits and demerits.

Table 1: Existing cold storage technologies in India [24]

Technology	**Initial cost Rs. In Lacs/TR**	**Advantages**	**Disadvantages**
Vapour Compression Refrigeration System (VCRS)	1.75 to 4	• Ideal for small applications • Simple in operation • Less maintenance	• High initial cost • High operating cost • Higher operating cost if run on a generator during unreliable power supply (very common in rural areas)
Vapour Sorption Refrigeration System (VSRS)	2.9 to 4.7	• High energy storage density • Capable of using industrial waste heat	• Very high initial cost • Costlier than a VCR system • Technology not feasible even for large capacity
Evaporative Cooling System (ECS)	3.3 (combined with VCRS)	• Minimal initial and running costs if only ECS is used • No electricity needed	• ECS alone cannot maintain the temperature in the range of 0 °C to 5 °C • Needs to be used in hybrid mode with other technology, causing cost implications

As observed from Table 1, cold storage with VCRS is a promising technology for small applications like micro cold storage for farm-gate applications. Hence, the inclusion of renewable energy along with the incorporation of hybrid energy storage for a VCR system is worth investigating. To comprehend the state of research in the current scenario, a Scopus-based bibliometric analysis was carried out using keywords "Cold Storage", "Solar", "Phase change materials", and "Battery", resulting in 38 publications in the last 15 years, with only 4 works specific to India. Figure 2 shows the representation of the country-wise analysis as obtained from the Scopus database, thus emphasising the need for hybrid storage facilitated cold room development, especially for perishable items like fruits and vegetables. The design of decentralised cold storage is thus an urgent need in remote areas of an agriculture-based country like India [5].

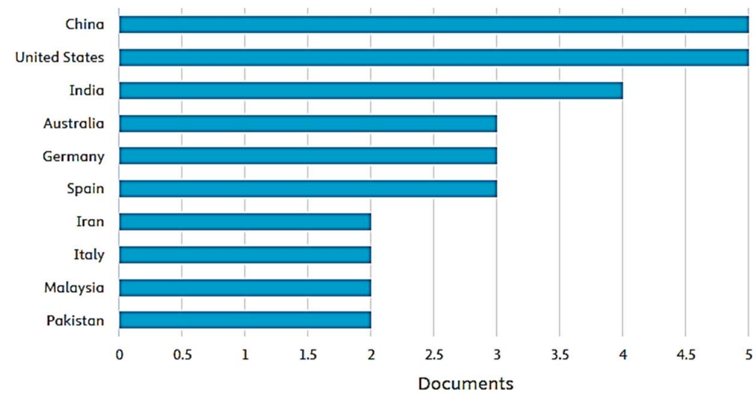

Figure 2: Country-wise analysis from the Scopus database of studies conducted on cold room with hybrid storage

This study proposes to develop a mathematical model for a cold storage, working on vapour compression refrigeration system using solar power with battery and thermal (hybrid) energy storage. Model simulation is then undertaken for a given set of weather conditions to obtain a set of feasible options for system parameters, namely solar PV rating and battery capacity.

This work aims to contribute by achieving the following objectives:

- Development of a mathematical model for sizing solar photovoltaic (PV) and battery storage for meeting specified demand based on given resource data that will be beneficial to the system designers in selecting an optimum combination for the integrated system.
- Contribution towards sustainability and growth through Sustainable Development Goals: SDG-7, on affordable and clean energy, by reducing dependency on thermal power plant-based grid electricity.

The following section discusses the methodology undertaken to carry out this work with subsequent sections elaborating on the same.

Methodology

The sizing and optimisation procedure is undertaken as shown in Figure 3. Cold room load estimation is carried out and the corresponding resource data is collected. A mathematical model is then developed based on the energy balance of the integrated system. This model is simulated over a specified time horizon (for eg. one day, one month etc.) subject to system constraints to obtain a set of feasible options through generation of the design space. Finally, optimum of the various combinations of solar photovoltaic and battery capacity for a given compressor and thermal storage is obtained.

Figure 3: Methodology adopted for sizing and optimization

The subsequent sections elaborate on the detailed methodology of the work.

Load estimation of the cold room system

The first step in carrying out the modelling and system simulation of the cold room is to comprehend the dynamic nature of the heat load the cold room has to cater throughout the day. This aids in understanding of the compressor run time, which is the power consuming device in the integrated system. The load on the storage is dependent on various factors like transmission load, infiltration load, product load and other miscellaneous loads. Transmission load occurs across the wall/floor/roof, infiltration load is mainly due to door openings for loading/unloading of product, while product load is due to fresh product loaded into the cold room, along with the respiration load of the already stored product. The miscellaneous load is due to the electrical appliances like fan and lighting load inside the cold room. The procedure to calculate the heat load is elaborated in Table 2. Based on the estimated load and the PCM charging requirement of the system, the compressor rating P_{comp} for a given cold room system is evaluated.

Table 2: Steps in heat load estimation

Heat load through transmission -walls, floor and roof		
Heat transmitted through walls	Q_w (W)	U_w x A_w x $CLTD$
Heat transmitted through floor	Q_{fl} (W)	U_f x A_f x $CLTD$
Heat transmitted through roof	Q_r (W)	U_r x A_r x $CLTD$
Total	Q_t (W)	$Q_w + Q_r + Q_{fl}$
Heat load through infiltration- Door opening		
Latent heat	$Q_{i,l}$ (W)	$m_a \times (h_o - h_i)$
Sensible heat	$Q_{i,s}$ (W)	$m_a \times h_{fg}\,(\omega_o - \omega_i)$
Total	Q_i (W)	$Q_{i,s} + Q_{i,l}$
Heat load through Product		
Product addition	$Q_{p,a}$ (W)	$m_{p,a} \times C_{pr} \times (T_{i,p} - T_{s,p})$
Stored product-respiration	$Q_{p,r}$ (W)	$m_{p,r} \times HoR$
Total	Q_p (W)	$Q_{p,a} + Q_{p,r}$
Heat load through other electrical equipment		
Fan	Q_f (W)	Fan rating
Lighting	Q_l (W)	Tube rating
Others	Q_o (W)	Miscellaneous
Total	Q_e (W)	$Q_f + Q_l + Q_o$
TOTAL HEAT LOAD ***(with 10% FOS)***	**Q_{total} (W)**	$(\boldsymbol{Q_t} + \boldsymbol{Q_i} + \boldsymbol{Q_p} + \boldsymbol{Q_e}) \times \mathbf{1.1}$

Mathematical model of integrated VCR-PCM-PV-Battery system

The integrated system consists of broadly two subsystems, viz, the thermal and electrical subsystems. The thermal subsystem consists of the vapour compression refrigeration system with thermal battery, and the electrical system encompasses the solar photovoltaic panel with the electrical battery along with the inverter. The compressor runs the cold room, which is driven by the solar photovoltaic panel during the sunshine hours and also charges the PCM after the cold store load is met. The excess solar energy available from the panels is stored in the battery and is used during the non-sunshine hours. The system hence operates to be a stand-alone system which is independent of the grid energy. The system schematic is shown in Figure 4.

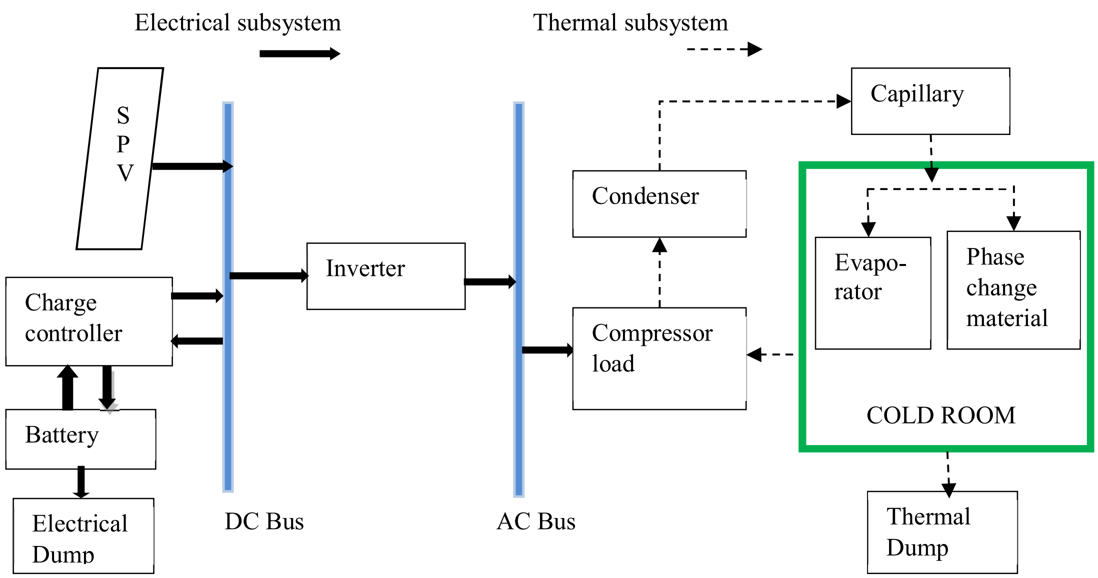

Figure 4: Schematic of the integrated system

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The mathematical model of the integrated system is developed from the overall energy balance of the system as stated in equation (1)

$$B(t+\Delta t) = B(t) + \left[P_{PV}(t) - P_{comp}(t).f_i - D(t)\right] \times f \times \Delta t \tag{1}$$

where, $B(t)$ is the energy stored in the battery at given time t, $B(t + \Delta t)$ is the energy stored in the battery after time step Δt, $P_{PV}(t)$ is the energy supplied by solar photovoltaic panel during time t, $P_{comp}(t)$ is the electrical/compressor load that needs to be catered to at given time t, f_i is the inverter efficiency factor. $D(t)$ is the dump considered as the non-negative variable and f is charging/discharging efficiency factor of the battery that represents the energy lost due to bi-directional process of battery and is given by equation (2)

$$\begin{aligned} f &= \eta_c \quad \text{when } P_{PV}(t) \geq P_{comp}(t) \\ f &= \frac{1}{\eta_d} \quad \text{when } P_{PV}(t) < P_{comp}(t) \end{aligned} \tag{2}$$

The battery capacity required for a given solar PV rating and compressor size can be calculated by simulating equation (1) over the entire time horizon. All possible combinations of the solar PV rating and the corresponding battery capacity that fulfil the electrical load criterion for the functioning of the cold room can be identified. The set of feasible combinations of the solar PV and battery sizing is obtained by plotting the sizing curve. The procedure for the same is explained in the following section.

System simulation and design space generation

The sizing curve helps to identify the minimum battery capacity required for the corresponding PV panel and compressor rating. To obtain the sizing curve, initially, the cooling demand as elaborated in the previous section is calculated over a time horizon. The energy stored in the battery at the end of each time step Δt is obtained by solving equation (1) with the assumption that no excess energy is generated and hence dumped energy is zero for the entire time horizon ($t = 0$ to T). The required inputs for solving equation (1) are the load data that helps to determine the compressor rating and the resource availability data over the stated time horizon. The nominal charge/discharge efficiencies of the battery bank converter system are also input parameters. To obtain the minimum battery rating, a numerical search is carried out over the time horizon that satisfies the energy balance equation (1) along with the additional constraints where initial battery storage is zero (equation 3) and dump energy assumed to be a non- negative variable (equation 4).

$$B(t=0) = 0 \tag{3}$$

$$D(t) \geq 0 \tag{4}$$

If the final stored energy level at the end of the time horizon is negative i.e. if $B(t = T) < 0$, then the power source is insufficient to meet the load. A positive stored energy is indicative of the capability of the power source to cater to the demand. The excess energy $B(t = T)$ can be dumped at various instants to reduce the peak of the stored energy. The energy to be dumped D is then calculated using equation (5).

$$D = B(t=T) - B(t=0) \tag{5}$$

The required battery capacity B_{cap} is further calculated using equation (6).

$$B_{cap} = \frac{B}{DOD} \tag{6}$$

where, DOD is depth of discharge of the battery bank viz is the limit beyond which the battery should not discharge and B is the amount of energy stored in the battery and is calculated using equation (7).

$$B = B_{max} - B_{min} - D \tag{7}$$

For simulation over the time horizon, equation (7) provides the amount of energy stored in the battery by reducing the dump energy (D). D is the power dumped whenever excess energy is available in the event of battery being fully charged. However, in most practical applications, through proper control over energy generation, excess power itself is not produced.

The proposed procedure provides the value of the minimum battery storage capacity for a given PV panel rating. From designers' perspective, it is important to identify all the feasible combinations of the PV rating and its corresponding battery capacity. The simulations to obtain the minimum storage capacity are carried out for different values of PV panel ratings. For each value of PV rating considered, the corresponding minimum battery capacity is obtained by evaluating the required storage capacity (equation 6). The optimization variables are the initial battery energy, $B(t = 0)$ and $D(t)$. The combinations of the different PV ratings and its corresponding minimum battery requirements is plotted on the PV rating vs. battery capacity diagram that is joined to obtain the sizing curve as represented in Figure 5. The sizing curve is the locus of the minimum battery capacity for corresponding PV panel rating. This curve divides the plot of into two regions. The space above the sizing curve is the feasible region and any combination of PV and battery in this region represents a feasible design option. The sizing curve along with this space is the design space for a given problem. The system designer can choose a suitable combination of solar PV rating and battery capacity in the design space for a corresponding compressor size which will ensure that the cooling demand is met at all times.

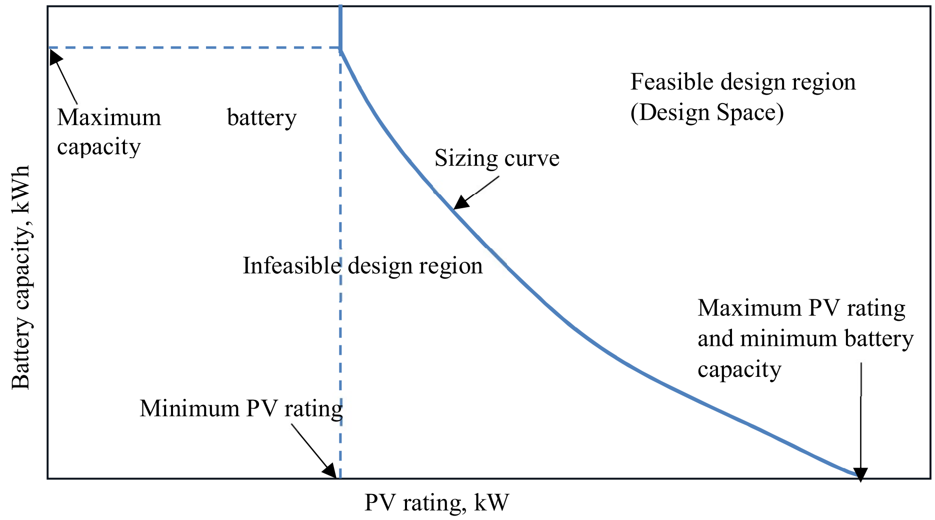

Figure 5: Typical sizing curve and design space for a photovoltaic-battery storage integrated system for specific compressor rating

Further, the feasible options obtained are subjected to optimization based on specified objective and is elaborated in the following section.

System optimisation

Identification of the design space provides the entire range of configurations that can cater to the load. These configurations can be used to select the optimum configuration based on the desired objective. The objective function used in this work is the cost of energy (*CoE*). The objective function, which accounts for capital as well as operating cost, is to be minimised. The total annual cost is the sum of annualised capital cost (*ACC*) and the annual operational and maintenance cost (*AOM*) of the system. If E_{gen} is the energy generated annually, then the cost of energy can be represented as in equation (8):

$$CoE = \frac{ACC + AOM}{E_{gen}} \tag{8}$$

The annualized capital cost is calculated using equation (9):

$$ACC = \sum_i C_{0i} \times CRF_i \tag{9}$$

where capital recovery factor (*CRF*) is the function of discount rate (*d*) and the component life (*n*) and it is evaluated for the i^{th} component as shown in equation (10):

$$CRF_i = \frac{d(1+d)^{n_i}}{(1+d)^{n_i} - 1} \tag{10}$$

C_{oi} is the capital cost of the i^{th} system component, which includes cold room, solar PV array, inverter and battery bank. The annual operational and maintenance cost is taken to be 1% of the capital cost [25].

The methodology adopted in this work for design space generation and optimisation is explained through an illustrative example in the subsequent section.

Illustrative example

The location taken for this illustration is Pune, Maharashtra, India. The load profile for a cold room in Pune is depicted in Figure 5 for a representative day (time horizon) in April, due to the availability of maximum sunshine hours. The maximum and minimum loads are 0.49 and 0.36 kW corresponding to maximum and minimum surrounding temperature of 37°C and 21°C over the day respectively. The heat load is calculated, as elaborated in Table 2, for storing tomatoes in a 3.4m^3-sized cold room, which is the minimum required space for the storage of 1MT of product, according to National Horticulture Board (NHB), India.

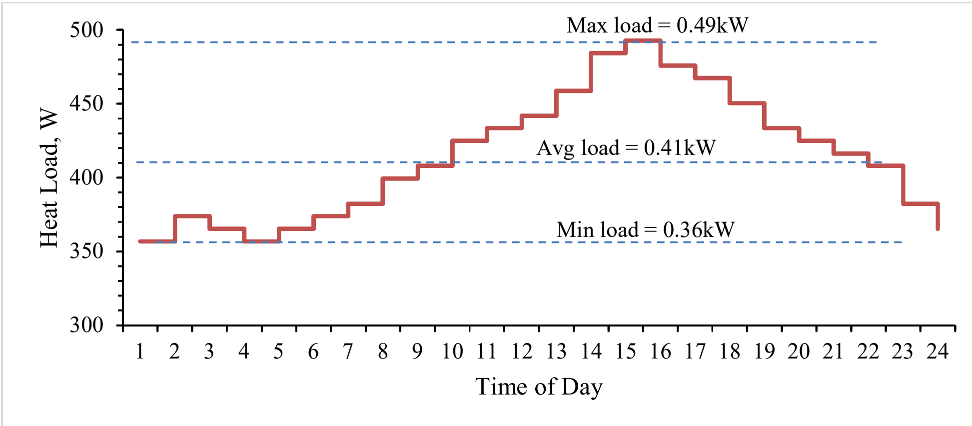

Figure 5: Load profile on a typical day

The hourly variation of the solar insolation for the same is calculated using the data from the MNRE Solar Radiation Handbook [26]. This is represented in Figure 6, which depicts maximum energy available is 0.93 kW at noon. The procedure to obtain the sizing curve is then undertaken, for which the parameters used are stated in Table 3.

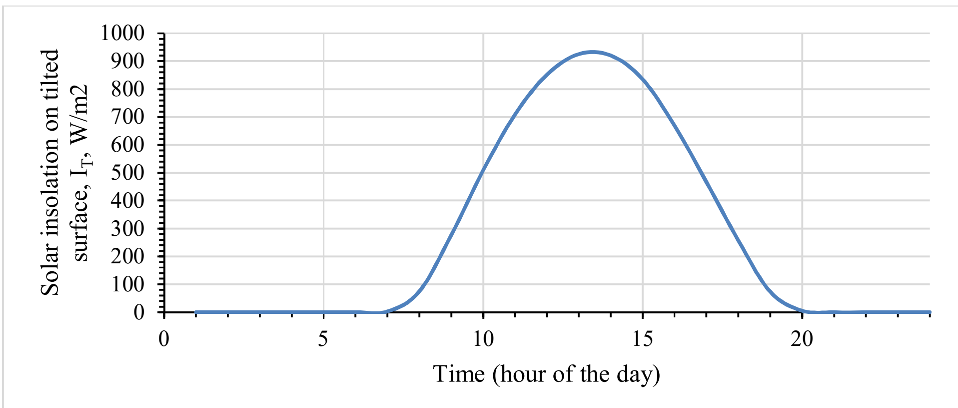

Figure 6: Solar Insolation falling on tilted surface on the representative day

Table 3: Input parameters used in the system sizing [27]

Sr. No	Parameters	Values
1.	Ambient Temperature for Pune	20 -37 °C
2.	Solar PV Panel efficiency	19%
3.	Inverter conversion efficiency	90%
4.	Battery charging efficiency	85%
5.	Battery discharge efficiency	85%
6.	Depth of discharge	70%

The power generated from the PV array is calculated using a constant efficiency model as stated in equation (11) [25]

$$P_{PV} = \eta_{PV} A_{PV} I_T \tag{11}$$

where η_{pv} is the photovoltaic system efficiency, A_{pv} is the total array area (m^2) and I_T is the total radiation incident on the tilted panel array (W/m^2). The solar array area is varied from zero to $70m^2$,which is the maximum limit specified for a solar-powered cold storage of less than 2MT storage capacity by the Ministry for New and Renewable Energy (MNRE) [28]. The minimum battery capacity required to meet the cold room load is determined to generate the sizing curve for the system. The sizing curves obtained for various compressor ratings that can provide thermal backup for 6 hours are shown in Figure 7, which is plot of PV panel rating vs. battery capacity. It is observed that as the PV array rating rises, the minimum battery capacity required to meet the load reduces. Since cold storage system is a continuously running device, it is understood that as the PV rating increases, the battery gets charged continuously and often to its full capacity. As the system load is catered directly by solar PV, the need for storing energy decreases, resulting in reduced battery capacity. However, it may be noticed that this drop in the battery capacity is not significant for the compressor ratings between 0.94 kW and 0.96 kW, which lie in the mid-range of the selected compressor powers capable of providing 6 hours of thermal backup.

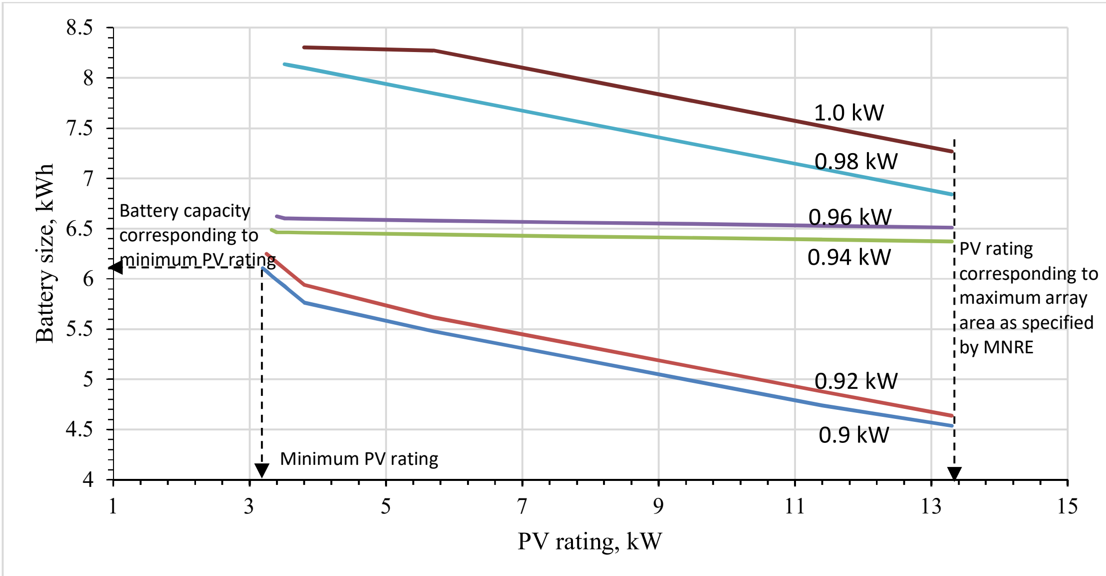

Figure 7: Sizing curves for various compressor ratings for minimum 6 hours of thermal backup

Every point on the sizing curve is a feasible design option, and the locus of all such points together constitutes the design space. The multiple lines are indicative of the different sizing curves corresponding to the change in compressor rating for thermal backup period of 6 hours and more. It can be seen that for every compressor rating there exists a minimum solar PV rating that is essential to satisfy the load. Also, for this minimum PV rating, there exists a corresponding minimum battery capacity that will provide the necessary storage. Figure 7 represents this point for 0.9 kW compressor power where the minimum PV rating is 3.25 kW and the minimum battery capacity is 6.2 kWh. Any combination of these parameters above the minimum specified will be a feasible option from which the designer may choose the optimum. It is also observed that for a given solar PV rating, as the compressor size increases, higher battery capacity is required. The reason for this is the rise in electrical demand with increase in compressor size.

Table 4: Economic parameters used in the system optimization [24], [29]

Sr. No	Parameters	Values
1.	Discount rate, d	10%
2.	Cold room life	20 years
3.	PV system life	20 years
4.	Battery bank life	5 years
5.	Inverter life	10 years
6.	Cost of cold room	4,00,000 Rs/MT
7.	Cost of PV system	70,000 Rs/kW
8.	Cost of battery bank (Lead Acid)	25,000 Rs/kWh
9.	Cost of inverter	18,000 Rs/kW

The integrated system is optimised by evaluating the objective function, cost of energy (*CoE*), for the feasible options obtained through the design space for 0.9 kW of compressor rating. The economic parameters used for system optimisation are tabulated in Table 4. Figure 8 shows the *CoE* calculated for different combinations on the sizing curve. It is observed that *CoE* decreases with an increase in solar PV rating and increases with an increase in battery capacity.

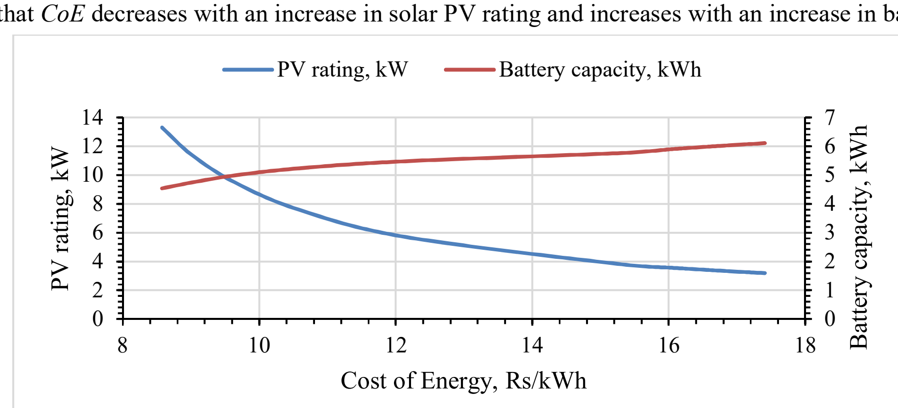

Figure 8: Cost of Energy corresponding to design space generated for 0.9kW compressor rating

The minimum *CoE* obtained is 8.5 Rs/kWh for the combination of a compressor rating of 0.9 kW for 13.3 kW PV panel rating with a battery capacity of 4.34 kWh. The optimum point so obtained is highlighted in Figure 9.

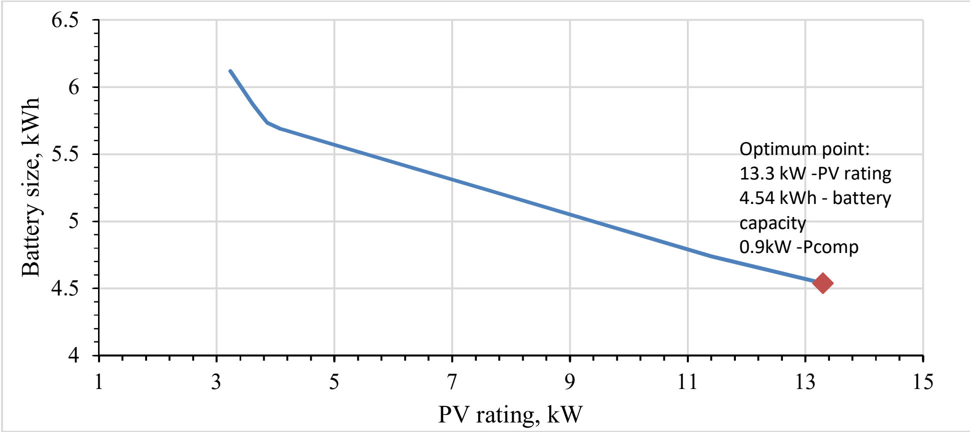

Figure 9: Optimum point depicted on the design space generated for 0.9 kW compressor rating

Impact of PCM integration

Experimentation was carried out on a 3.4m^3 cold storage with tomatoes as the testing product. The prescribed temperature to be maintained for proper storage of tomatoes is in the range of 8 to 14^{o}C according to NHB standards. Accordingly, the PCM selected was OM 8 (commercial product from OPALKEM, India) which has a phase change temperature between 7-8^{o}C. Its base material is organic in nature with a latent heat of 154kJ/kg. 100kg of this PCM was used to maintain the desired temperature in the cold room for a period of 6 hours when compressor is non-operational providing the required thermal backup. Temperature profile of the air inside the cold room and the corresponding PCM temperature while discharging during the conduction of the test is shown in Figure 10. The data represented is as recorded between 28th March 2025,11.49pm and 29th March 2025, 9.49am. While the cold room temperature rise is restricted to 4.3^{o}C, the PCM absorbs the energy causing a 4.1^{o}C increase in its temperature maintaining the desired temperature for 430 minutes.

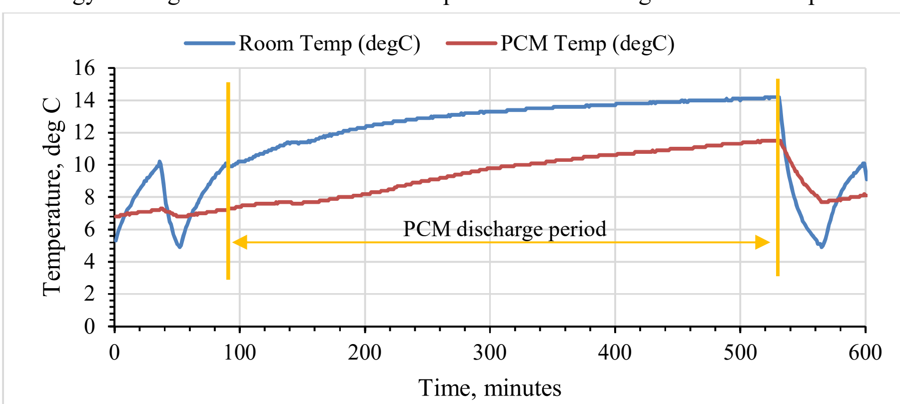

Figure 10: Temperature profile of cold room air and corresponding PCM temperature

During the testing, the energy consumption of the cold room was observed and analysed as shown in Table 5. The energy saving potential is calculated based on the reduction achieved in the compressor run time during the PCM discharge hours. Since the compressor does not operate during the 6 hours of back up period, the savings achieved is 2.4 kWh/day.

Table 5: Comparison of energy consumption with and without PCM

Sr. No.	Parameters	Without PCM	With PCM
1.	Product tested	Tomatoes	Tomatoes
2.	Set temperature	8-13^{o}C	8-13^{o}C
3.	Set relative humidity	90-92%	90-92%
4.	PCM charging energy (using renewable source- Solar PV)	-	2.45 kWh/day
5.	PCM discharged energy (6 hours)	-	2.4 kWh/day
6.	Average energy consumed	3.9 kWh/day	1.5 kWh/day
7.	Savings in energy	-	2.4 kWh/day

It is seen that the energy consumed in the absence of PCM is 3.9 kWh/day as the compressor runs to cater to cold storage load during the entire day. This indicates that the energy consumption drops to 38% with inclusion of PCM as a thermal storage. The energy consumed to charge the PCM was recorded to be 2.45 kWh/day. This however is excluded from the calculation, as this energy is generated through renewable source i.e. PV solar panel and hence no grid energy is used for the decentralised cold room.

Conclusion

The design and development of stand-alone green energy-based cold storage is one of the emerging solutions to reduce dependency on fossil fuel-based energy and help to mitigate environmental challenges caused by it. Few such cold rooms are being taken for research work; however, it is observed that the integration of hybrid storage viz combination of thermal and electrical storage remains underexplored. This study proposes the development of a mathematical model for the sizing of VCR-PCM-PV-Battery based cold room. Through design space approach a set of feasible options is obtained for the system parameters. It is observed that for a given compresor rating, there exists a corresponding minimum solar PV rating necessary to meet the load. Also for this minimum PV capacity, a minimum battery storage capacity exists to ensure consistent energy supply. The understanding of this interdependency between compressor power, solar PV rating and battery capacity is vital for designing off-grid cold room with hybrid storage. Further,in this work an optimum combination of the design parameters is identified through minimising the Cost of Energy (*CoE*),. The proposed methodology is illustrated through a case study for a 3.4 m^3 cold room installed in Pune, Maharashtra, India. For an average load of 0.41 kW for a typical day in the month of April, the system was sized, and the design space was generated. To obtain thermal backup for a period of minimum 6 hours, the optimum parameters were found to be 0.9kW of compressor rating to be run by solar PV rating of 13.3kW with a battery backup of 4.34kWh. The *CoE* was minimum for this combination which was evaluated as 8.5 Rs/kWh. Experimental results highlighted a reduction of 38% in the energy consumption with PCM integration in a decentralised cold room. Demonstration of this methodology for real-time application, through the development of a physical cold room, is the anticipated future work. Inclusion of decision making tools like TOPSIS can be explored in future for optimization. Integration of machine learning for data collection and analysis for shelf-life prediction of the stored product is also a prospective endeavour.

Nomenclature

A_{pv}	Solar PV array area, m^2
A_w	Cold room wall area, m^2
A_r	Cold room roof area, m^2
A_{fl}	Cold room floor area, m^2
B	Energy stored in battery, kWh
B_{cap}	Battery capacity, kWh
$CLTD$	Cooling load temperature difference, K
C_{pr}	Specific heat of product, kJ/kgK
C_{oi}	Capital cost of the i^{th} system component, Rs
d	Discount rate, %
D	Power dumped, kW
DOD	Depth of discharge
E_{gen}	Energy generated annually, kWh/year
f	Battery charging / discharging efficiency factor
f_i	Inverter efficiency factor
h_i	Enthalpy of inlet air, kJ/kg
h_o	Enthalpy of outlet air, kJ/kg
h_{fg}	Latent heat of moisture, kJ/kg
HoR	Heat of Respiration of product stored, W/kg
I_T	Total radiation incident on the titled panel array, W/m^2
m_a	Mass of air, kg
$m_{p,a}$	Mass of fresh product added, kg
$m_{p,r}$	Mass of existing product in cold room, kg
n	Component lifetime, year
η_c	Battery charging efficiency
η_d	Battery discharging efficiency
η_{PV}	Photovoltaic system efficiency
P_{comp}	Compressor rating, W
P_{PV}	Solar photovoltaic rating, kW
Q_w	Heat transmitted through walls, W
Q_{fl}	Heat transmitted through floor, W
Q_r	Heat transmitted through roof, W
Q_t	Transmission heat load, W
Q_i	Infiltration heat load, W
$Q_{i,s}$	Infiltration heat load due sensible heat, W
$Q_{i,l}$	Infiltration heat load due to latent heat, W
Q_p	Product heat load, W
$Q_{p,a}$	Heat load due to product addition, W
$Q_{p,r}$	Heat load due to product respiration, W
Q_e	Electrical heat load, W
Q_f	Fan heat load, W
Q_l	Heat load due to lighting, W
Q_o	Heat load due to other electric devices, W
Q_{total}	Total heat load, W
t	Time, h
Δt	Time step for simulation, h
T	Time horizon, h
$T_{i,p}$	Product initial temperature, K
$T_{s,p}$	Product stored temperature, K
U_w	Wall's overall heat transfer coefficient, W/m^2K
U_{fl}	Floor's heat transfer coefficient, W/m^2K
U_r	Roof's overall heat transfer coefficient, W/m^2K
ω_i	Humidity of air inside cold room, kg/kg moist air
ω_o	Humidity of ambient air, kg/kg of moist air

Abbreviations

ACC	Annualized capital cost, Rs/year
AOM	Annual operational and maintenance cost, Rs/year
CoE	Cost of energy, Rs/kWh
CRF	Capital recovery factor, $year^{-1}$
ECS	Evaporative Cooling System

MNRE	Ministry for New and Renewable Energy
NHB	National Horticulture Board
PCM	Phase change materials
PV	Photovoltaic
SDG	Sustainable Development Goals
VCRS	Vapour Compression Refrigeration System
VSRS	Vapour Sorption Refrigeration System

Disclosure on Use of AI

No AI technology is used in the generation of manuscript or figures and tables of this work.

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