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Economic feasibility of implementing thermoelectric cooling systems

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Abstract
Thermoelectric coolers utilizing peltier effect offer a promising solution for cooling applications. This paper explores the operational principles and economic feasibility of thermoelectric coolers, focusing on the Peltier effect as the underlying mechanism. the paper discusses the integration of thermoelectricity with photovoltaic power for diverse applications such as workplace comfort, refrigeration, and power generation. Economic analyses highlight the viability of thermoelectric systems, particularly in remote regions with intermittent electricity supply. Comparison with conventional refrigeration methods reveals the potential cost-effectiveness of thermoelectric solutions, albeit with considerations for initial investment and operational expenses. The findings contribute to advancing sustainable cooling technologies and inform decision-making processes for adopting thermoelectric solutions in various contexts.

Keywords: Thermoelectric coolers, peltier effect, economic feasibility, photovoltaic integration, remote regions, sustainable cooling technologies

Introduction
The direct conversion of electric current into heat or the generation of electricity from a temperature gradient through a thermocouple is recognized as the thermoelectric effect. Managing temperature variations to generate power is an effective way of using waste heat. The operation of the thermoelectric cooler is based on the Peltier effect, which is basically the integration of thermally conducting ceramic plates on both sides with pairs of n- and p-type semiconductor thermoelements connected thermally in parallel and electrically in series. The system requires no refrigerant since the Peltier effect transforms the incoming electric current into a temperature gradient and heat transfer is accomplished by electrons moving from the heat source to the heat sink (Daghigh and Khaledian, 2018) [5]. The schematics of a thermoelectric module employed for refrigeration and power generation is demonstrated in Fig. 1.

Another form of sustainable energy that can be used for workplace comfort and for cooking, heating, cooling, and refrigeration is thermoelectricity in conjunction with photovoltaic power. According to Chen *et al*., (2014) [4] and Afshari *et al*., (2022) [1] the Peltier module perform noiseless operation, has a longer lifespan, compact size, lightweight, portable, high reliability, low-cost production, less maintenance with non-generation of harmful gases as a mini-refrigerator for preserving foods and drugs in remote places.

The alternative refrigeration technologies are required in developing countries, where electricity supplies are intermittent. PV panels can be used to power thermoelectric devices, which need a DC source of electricity in order to generate cooling within cabinets. It is portable and may be used at a sale or medical counter or stored on site. In hot and humid regions, the storage of farm produce and medicine is crucial task. About 30–35% of the losses of horticultural produce could be reduced by refrigerated containers using solar PV panels to power the thermoelectric cooling devices. Vaccines have to be carried long distances, stored in remote places and during this period the temperature has to be maintained within certain specified values.

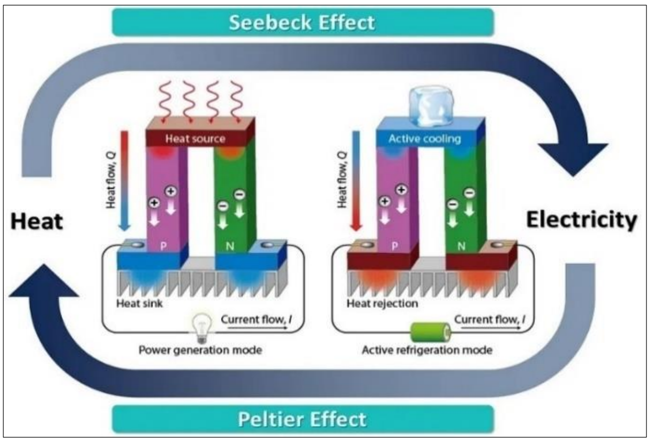

Fig 1: Schematic illustrations of a thermoelectric module for (a) Power generation (Seebeck effect); (b) Active refrigeration (Peltier effect)

The economic feasibility of thermoelectric cool chamber was studied in current investigation. The reviews on disparity and need of electricity in remote areas of Maharashtra and India, parameters to operate thermoelectric cooling systems and performance of thermoelectric refrigeration systems were further reported.

Review of Literature

Suryawanshi (2014) [14] conducted an analysis of the developmental status across the Jawahar, Mokhada, Vikramgad, and Vada tahsils within the rural Thane district of Maharashtra. The findings revealed an escalating disparity from the southwest to the northeast of the selected region, with the majority of settlements indicating a low to very low level of development. These areas have experienced notable deficiencies in socio-economic advancement, including inadequate transport connectivity, healthcare services and low literacy rates. Addressing the challenges faced by these disadvantaged regions requires the formulation of strategies through comprehensive planning and inclusive community engagement.

Palit and Bandyopadhyay (2017) [11] documented that while in 1981, 63% of urban households had access to electricity, merely 15% of rural households in India were electrified. Agrawal *et al.* (2020) [15] conducted a residential energy survey focusing on electricity access and usage in Indian households, revealing a significant increase in the proportion of rural households using electricity as their primary lighting source, from 44% in 2001 to 96% in 2020. Despite substantial progress, as of 2023, 2.4% of Indian households remained unelectrified, with a concentration of such households primarily in the rural regions of Uttar Pradesh, Madhya Pradesh, Rajasthan, Haryana, and Bihar.

Basavraj (2020) [2] discussed the performance parameters of Thermoelectric Coolers (TECs), emphasizing key metrics such as the figure of merit, cooling capacity of peltier modules, and coefficient of performance. An effective thermoelectric material should exhibit a high Seebeck coefficient, elevated electrical conductivity, and low thermal conductivity. However, the efficiency of TECs is constrained to 10-15%, with materials possessing a ZT value exceeding 0.5 deemed practical. TECs face challenges, including limitations in size for heat pumping and internal joule heating, leading to inferiority compared to compressor-based cooling systems.

Martinez *et al.* (2013) [16] addressed challenges in TEC operation within refrigeration systems, advocating for measures such as supplying minimum voltage to prevent heat recirculation and ensuring proper insulation and matching of heat sink dimensions during TEC assembly installation to minimize heat leakage.

Gokcek and Sahin (2017) [8] devised a 0.065 m^3 refrigerator employing two TEC1-12709 thermoelectric modules with mini-channel heatsinks and heat dissipaters. Experimentation with different voltages and cooling water flow rates over a 2-hour period revealed an interior temperature of 2 °C at 0.8 L/min and -0.1 °C at 1.5 L/min. The COP values were 0.19 and 0.23 after two minutes of chilling, reaching approximately 0.41 after 25 minutes at 1.5 L/min and 8 V. Higher flow rates correlated with decreased internal temperatures.

Dongre *et al.* (2018) [17] developed a thermoelectric refrigerator with an 18 L volume using TEC1-12706 modules, achieving a chamber temperature reduction from 33 °C to 22 °C within 1 hour, with a slight rise in the hot side temperature.

Chavan *et al.* (2021) [3] introduced a liquid-cooled thermoelectric refrigeration (LCTR) system for 100 L capacity storage of summer fruits and vegetables, significantly reducing physiological loss in weight and extending shelf life by 7 to 13 days compared to ambient storage.

Sankar *et al.* (2022) [13] designed a low-cost seed storage unit (SSU) utilizing a TEC to maintain temperatures between 15 °C and 18 °C, preserving seed viability above 80% over 18 months across various agro-climatic locations.

Materials and Methods

The developed thermoelectric cool chamber (TCC) comprised of SPV Panel, solar charger controller, battery, Pulse width modulated (PWM) power supply, solar charge/ MPPT controller, thermoelectric module with heat sink and insulated box. The schematic of components assembly of developed thermoelectric cool chamber is shown in Fig. 2.

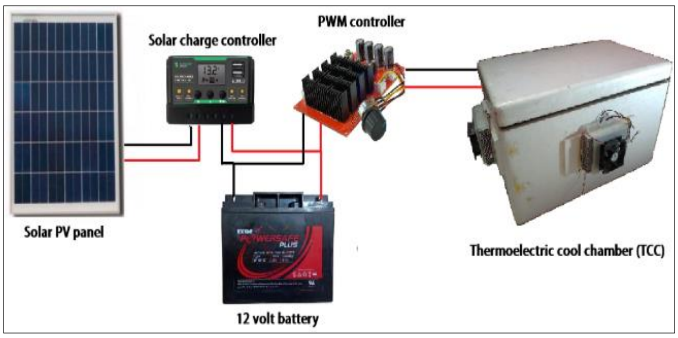

Fig 2: Schematic of components assembly of developed thermoelectric cool chamber

The cost economic of solar photovoltaic operated thermoelectric cool chamber was worked out to determine unit cost of energy consumed per kWh. Also, economic indicators were calculated to find its feasibility to run as a business for cold storage of potatoes. The economic feasibility of solar photovoltaic operated thermoelectric cool chamber was calculated by considering initial investment, operating cost and average repair and maintenance cost of the system. The capital cost, variable cost, fixed cost, total cost, revenue and net profit were basic components of economic analysis of any business.
The economics of cooling operation changes as per the product kept in cold chamber as well as other factors. The economics was calculated for cooling of potatoes by solar photovoltaic operated thermoelectric cool chamber and vapour compression type cold storage. The cost economics was computed following the methodology of Eltawil and Samuel, 2007 [7]; Kart and Demircan, 2015 [9].

Capital cost
The capital cost includes cost of construction of thermoelectric cool chamber, solar panels, battery, wiring, power supply unit and other miscellaneous items with more than one year life span.

Total variable cost
The total variable cost was the day-to-day expenses incurred for the working of the cool chamber is termed as operating cost or variable cost. The expenses on raw material, instruments, transportation, wages, operation maintenance etc. were the major components of variable cost of cold stored raw potatoes.

Depreciation
Depreciation was declined in the value of given asset as a result of the use, wear and tear, accidental damage and time obsolescence.

Depreciation = (Purchase price of the asset- Salvage / Junk value) / Expected life

Total cost
The total expenditure per annum was calculated by adding the fixed cost and variable cost.

Revenue
The revenue was the total price received from the cold stored potatoes throughout the year.

Net profit
The net profit was obtained by subtracting total cost from the revenue of the year.

Unit cost of electricity (USE_{PV})
The unit cost of electricity produced by a PV system can be calculated as:

$$USE_{PV} = \frac{\text{Levelized annual cost of PV system}}{\text{Annual electricity output from the PV system}}$$

The levelized annual cost of the PV system comprises of annual capital recovery cost and annual costs of operation and maintenance, taxes and insurance etc. The annual capital recovery cost can be computed as a product of the capital cost, C and the capital recovery factor (CRF)

$$\text{Annual capital recovery cost} = C\left[\frac{d\,(1+d)^n}{(1+d)^n - 1}\right]$$

Annual capital recovery factor for fuel (CRF_f) can be calculated with the following formula.

$$\text{Annual capital recovery factor for fuel } (CRF_f) = \frac{(d - i_f)/(1 + i_f)}{1 - \left[1 + \frac{(d - i_f)}{(1 + i_f)}\right]^{-n}}$$

Where,
d= Discount rate
i = Fuel inflation rate
n = Expected useful life
C = Initial cost of the investment

Economic indicators
Net present worth (NPW)
This was simply the present worth of the cash flow stream. Sometimes it is referred to as Net present value (NPV). NPW was an absolute measure but not relative.
NPW of project was estimated using the following equation.

$$NPW = \frac{P_1}{(1+i)^{t_1}} + \frac{P_2}{(1+i)^{t_2}} + \dots\dots + \frac{P_n}{(1+i)^{t_n}} - C$$

Where,
P_1= Net cash flow in first year
i = Discount rate
t = Time period and
C = Initial cost of the investment

Benefit- Cost Ratio (B-C Ratio)
Benefit-Cost Ratio (B-C Ratio) was calculated by comparing the present worth of costs with present worth of benefits. Absolute value of benefit- cost ratio will change based on the interest rate chosen. Following formula depicted the estimation of B-C ratio.

$$B - C\ Ratio = \frac{\sum_{t=1}^{n} \frac{B_t}{(1+r)^n}}{\sum_{t=1}^{n} \frac{C_t}{(1+r)^n}}$$

Payback period
The payback period is the number of years required for recovering the initial investment. The payback period is the time required for the system to pay for itself from energy cost savings. It was calculated by the following formula.

$$\text{Payback Period} = \frac{\text{Initial Capital Cost}}{\text{Annual Energy Cost Saving}}$$

Return on Investment (ROI)
Return on Investment is the percentage return on the initial investment over a given period.

$$\text{Return on Investment (ROI)} = \left[\frac{(\text{Net savings} - \text{Initial investment})}{\text{Initial investment}}\right] \times 100\%$$

Profitability index (PI)

The profitability index is the ratio of net present values of the cash flows to the initial capital expenditure (C_0). Assuming that all the capital expenditure is incurred in year zero, the profitability index (PI) is as follows.

$$PI = \frac{NPV}{C} = \frac{1}{C}\sum_{i=1}^{n}\frac{C_r}{(1+i)^n}$$

Where,
PI = Profitability index
NPV= Net present value of cash flows
C = Initial capital expenditure
C_r = Total capital required for the project

Internal rate of return (IRR)

In the computation of Internal rate of return (IRR), the time value of money was accounted. It is the discount rate at which the present values of the net cash flows are just equal to zero, i.e. NPW = zero. The IRR must be found out by trial and error with some approximation. The IRR was found out using the following equation.

$$\begin{bmatrix}\text{Internal rate}\\ \text{of return}\end{bmatrix} = \begin{bmatrix}\text{Lower}\\ \text{discount}\\ \text{rate}\end{bmatrix} + \begin{bmatrix}\text{Difference between}\\ \text{two discount rates}\end{bmatrix} \times \begin{bmatrix}\dfrac{\text{Present worth of the cash flow at the lower discount rate}}{\text{Absolute difference between the present worth of cash flow at two discount rates}}\end{bmatrix}$$

Levelized cost of energy (LCOE)

The levelized cost of energy is the per unit cost of energy produced by the system over its lifespan.

$$\text{LCOE} = \frac{\text{Total cost over lifespan}}{\text{Total energy production over lifespan}}$$

$$\text{LCOE} = \frac{(\text{Initial capital costs} + \text{Total operating costs})}{\text{Total energy production over lifespan}}$$

Results and Discussion

The cost economics for cooling system (0.087 m^3) SPV operated thermoelectric cool chamber was compared with 80 L conventional cold storage structure to reach the conclusion. The economic considerations were made for solar photovoltaic system, cooling system (0.087 m^3) SPV operated thermoelectric cool chamber and 80 L conventional cold storage structure.

A. Economic considerations for solar photovoltaic system

In the present analysis it was assumed that:
1. Discount rate is considered as 10%.
2. The general inflation rate is considered as 5%.
3. The present system was considered as stand-alone type solar photovoltaic operated thermoelectric cool chamber. The cost of SPV module was considered without subsidies because subsidies are available for grid connected SPV system.
4. The system is operated for 300 days annually considering rainy period in Konkan region.
5. The useful life of the PV modules are 20 years.
6. Storage batteries generally have shorter life span about 3 years than the PV array and will have to be replaced a number of times during the life of the system.
7. The lifespan of MPPT charge controller is assumed as 10 years.
8. Taxes and insurance costs are not to be paid.
9. The average SPV energy output is 6.8 kWh/day (340 Wp x 4 no. of modules for 5 hours).

A-1. Economic indicators for energy cost

Annual energy cost =
$\text{Average SPV energy output} \times \text{Unit cost of electricity} \times \text{No. of days per year} = 6.8 \times 10 \times 300 = \text{Rs.}\,20{,}400/-$
$\text{Energy consumption} = \text{Daily consumption by TCC unit} \times \text{No. of days per year} = (3720 \times 300)/1000 = 1116\ \text{kWh}$

$\text{Annual energy cost of saving} = \text{Yearly energy Generation} \times \text{Unit cost of electricity} = 2{,}040 \times 10 = \text{Rs.}\,20{,}400/-$

$\text{Payback period} = (\text{Initial capital cost})/(\text{Annual energy cost of saving}) = 90{,}700/20{,}400 = 4.45$ years

Assuming 10 years analysis period, the total energy cost saving over 10 years would be $= \text{Annual energy cost of saving} \times 10\ \text{Years} = 20{,}400 \times 10 = \text{Rs.}\,2{,}04{,}000/-$

Total operating cost
$= (\text{Labour and maintenance cost of SPV system} + \text{spares of TCC unit}) \times \text{Years} + \text{Battery cost}$
$= (\text{Rs.}\,1{,}617/- \times 10)$ + 32,000/- = Rs. 48,170/-

$\text{Net saving} = \text{Total energy cost saving} - \text{Total operating cost} = 2{,}04{,}000 - 48{,}170 = \text{Rs.}\,1{,}55{,}830/-$

Return on Investment
$$= \left[\frac{\text{Net saving} - \text{Initial investment}}{\text{Initial Investment}}\right] \times 100$$
$= [((1{,}55{,}830 - 90{,}700))/90{,}700] \times 100$ = 71.81%

Net present value
$$= \left[\frac{20{,}400}{(1+0.1)^0} + \frac{20{,}400}{(1+0.1)^1} + \dots\dots + \frac{20{,}400}{(1+0.1)^{10}}\right] - 90{,}700$$
$$= 1{,}45{,}758.49 - 90{,}700 = \text{Rs.}\,55{,}049.49/- \approx \text{Rs.}\,55{,}049/-$$

As NPV > 0, the investment is financially economical.

Levelized cost of energy (LCOE)
$$= \frac{(\text{Initial capital cost} + \text{Total operating cost})}{10 \times \text{Annual energy consumption}}$$
$$= \frac{(90700 + 48170)}{10 \times 2040}$$
= Rs. 6.81/- per kWh

B. Economic considerations for cooling system (0.087 m^3) SPV operated thermoelectric cool chamber

1. As per the calculation of cooling load the chamber is designed for cooling load of 111 W = 1.59 kcal/min = 0.03 TR
2. The electricity consumption of storage structure is 3.72 kWh/day
3. The structure is used for storage of 30 kg of potato. Considering bulk density of potato as 704.36 to 738.49 kg/m^3 (Patel *et al*., 2018) with 18- 20% space provided to improve air circulation and avoid moisture condensation on the stored commodity.
4. The lifespan of TCC unit is assumed as 30 years.
5. The raw potato cost is Rs. 10/- per kg.
6. Weight loss during storage due to transpiration, respiration etc. is considered as 6%.
7. The selling price of potato is Rs. 28/- per kg.
8. The running period of the cooling system is 300 days.
9. The initial investment being small is met from the farmers own resources.
10. No insurance and taxes are involved in the cooling system.

The economics of solar photovoltaic-operated TCC unit is summarized in Table 1. The economics of solar photovoltaic operated TCC unit for cooling potato is given in Table 2.

1. Daily consumption of TCC unit is 3.72 kWh.
2. Cost of electricity for cooling of 30 kg potatoes daily = 3.72 x 7.73 = Rs. 28.76/-
3. Cost of electricity for cooling of 1 kg potato = 28.76/30 = Rs. 0.96 /- kg *

Table 1: Economics of solar photovoltaic system for unit cost of energy generation

S.N.	Description	Amount, Rs.
1.	Capital cost of PV modules (340 Wp x 4 Panels)	50,400/-
2.	Capital cost of batteries (300 Ah, 12 V)	20,000/-
3.	Capital cost of MPPT charge controller (12V, 78 A)	5,000/-
4.	Labour and overhead charges (1% of capital cost)	
5.	Maintenance cost (1% of capital cost)	
	Annual cost calculations	
i)	Annualized cost of PV modules, Rs. = 50,400 x 0.11746	5,920/-
ii)	Annualized cost of batteries, Rs. = 20,000 x 0.40211	8,042/-
iii)	Annualized cost of MPPT charge controller, Rs. = 5,000 x 0.1628	814/-
	Total annualized cost of PV system	14,776/-
iv)	Annual labour and overhead cost, Rs. = 0.01 x 50,400	504/-
v)	Annual maintenance cost, Rs. = 0.01 x 50,400	504/-
	Total annual cost, Rs.	15,784/-
	Unit cost of PV electricity generation, Rs. /kWh = 15,784/ (6.8 x 300)	7.73/-

It was found that, the net saving at the end of 10 years of SPV system operation and net present value (NPV) was Rs. 1,55,830/- and Rs. 55,049/- respectively. The payback period for energy cost saved and return on investment (ROI) of SPV system was 4.45 years and 71.81% respectively. The levelized cost of energy was Rs. 6.81/- per kWh. The unit cost of PV electricity generation was Rs. 7.73/- (Table 5.1).

Table 2: Economics of solar photovoltaic operated TCC unit for cooling potato

S.N.	Description	Amount (Rs.)
A	Fixed cost	
	Cost of structure with installed TEC, PWM controller and Fan, C	15,300/-
	Life of TCC Unit, L (L= 30 years)	
	Salvage/ Junk value, S (S =10% initial cost)	1,530/-
	Depreciation per year = (C – S) / L	459/-
	Cost per kg of potato (considering 30 kg of potato to be stored) = Fixed cost per year/ Qty. of potato	15.30/-
B	Variable cost	
	Cost of electronic components (switch, fan etc.)	150/-
	Cost per kg of potato = Variable cost per year/ Qty. of potato	5/-
	Total cost of cooling TCC unit used for storage of potato	20.30/-
	Total break-even cost of cooling including raw potato cost	30.30/-
	Break-even cost considering 6% weight loss = 30.30/ 0.94	32.23/-
	Total cost of cooling 1 kg potato in TCC unit, Rs. per yr. = 32.23 + 0.96*	33.19/-

C. Economic considerations for 80 L conventional cold storage structure

The cost economics for 0.087 m^3 storage structure can be calculated for storage of horticultural produce under the following assumptions.

1. The structure is used for storage of 30 kg of potato. Considering bulk density of potato as 704.36 to 738.49 kg/m^3 (Patel *et al*., 2018) with 18- 20% space provided to improve air circulation and avoid moisture condensation on stored commodity.
2. The lifespan of conventional cold storage unit is assumed as 20 years.
3. The product is stored for 300 days.
4. The raw potato cost is Rs. 10/- per kg.
5. Weight loss during storage due to transpiration, respiration etc. is considered as 6%.
6. The sell price of potato is Rs. 28/- per kg.
7. The electricity consumption of 80 L conventional cold storage working on vapour compression refrigeration is 375 units (1 unit = 1 kWh) per year.

8. The unit price of electricity through grid is Rs. 10/- per kWh at commercial rate.
9. The total initial investment being small is met from farmer's own resources.
10. The cold storage structure has been placed on the farmers own premises and no rent is paid for the space.
11. No insurance and taxes are involved in the cold storage structure.
12. The farmer makes the arrangement of periodic ventilation of the structure and check-up the stored produce.
13. Dark condition was maintained inside the cold storage structure.

The economics of conventional cold storage unit for cooling potato is given in Table 3.

1. Electricity consumption of conventional cold storage unit is 375 kWh per year
2. Daily consumption by cold storage unit = 375/ 300 = 1.25 kWh
3. Cost of electricity for cooling of 30 kg potatoes daily = 1.25 x 10 = Rs. 12.50/-
4. Cost of electricity for cooling of 1 kg potato = 12.50/30 = Rs. 0.42 /- kg [#]

Table 3: Economics of conventional cold storage unit for cooling potato

S.N.	Description	Amount (Rs.)
I	**Fixed Cost**	
	Cost of conventional cold storage unit, C	10,000/-
	Salvage/ Junk value, (S = 0.10 x Principal cost)	1,000/-
	Depreciation = (C – S) / Lifespan	450/-
	Cost per kg of potato = Fixed cost per year/ Qty. of potato	15/-
II	Variable cost	
	Cost of spare parts	150/-
	Cost per kg of potato = Variable cost per year/ Qty. of potato	5/-
	Total cost of cooling of conventional cold storage for potato	20/-
	Total break-even cost of cooling including raw potato cost	30/-
	Break-even cost considering 6% weight loss = 30/ 0.94	31.91/-
	Total cost of cooling 1 kg potato in conventional cold storage, Rs. = 31.91 + 0.42 [#]	32.33/-

The cost of cooling 1 kg potato in SPV operated TCC unit was Rs. 33.19/- per year (Table 2) While the cost of cooling 1 kg potato in conventional cold storage unit is Rs. 32.33/- per year (Table 3).

D. Economic indicators for cooling potatoes in SPV operated TCC unit and conventional cold storage unit

The capital and variable cost incurred for cooling potatoes, the present worth of cash flow, income statement, expenditure statement and cash flow statements for SPV operated TCC unit for cool storage of potatoes and for conventional cold storage unit for cool storage of potatoes are calculated.

The economic indicators like net present value, pay-back period, benefit to cost ratio, profitability index and internal rate of return are presented in Table 4.

Table 4: Economic indicators for cooling of potatoes

Particulars	SPV-operated TCC unit	Conventional cold storage unit
Net present value (NPV)	6,53,427.17	7,35,714.71
Pay-back period	0.75	0.09
Benefit to cost ratio (BCR)	1.93	2.05
Profitability index	7.20	73.57
Internal rate of return (IRR)	82%	129%

It was found that the net present value of investment made in cooling raw potatoes in the solar photovoltaic operated thermoelectric cool chamber and in conventional cold storage unit were Rs. 6,53,427/- and Rs. 7,35,714/- respectively (Table 4). The pay-back period for solar photovoltaic operated thermoelectric cool chamber and in conventional cold storage unit for cooling potatoes was found to be 0.75 year and 0.09 year respectively. The benefit-cost ratio, profitability index and Internal rate of return calculated for solar photovoltaic operated thermoelectric cool chamber and in conventional cold storage unit are 1.93, 7.20, 82% and 2.05, 73.57, 129% respectively.

Conclusion

It was observed that, both systems though have positive NPV, lower pay-back period and higher financial metrics (benefit to cost ratio, profitability index and internal rate of return), the conventional cold storage unit for cooling potatoes appears to be more cost effective than the solar photovoltaic operated thermoelectric cool chamber.

It was known that solar PV installations requires upfront costs for equipment including solar panels, inverters, batteries and labour which are relatively high compared to traditional grid connections. However, the prices of solar panels have been decreasing over the years due to technological advancements, making solar energy more competitive. In remote areas, extending the electrical grid can be prohibitively expensive due to the need for extensive infrastructure. Solar PV system provide a decentralized solution, eliminating the need for extensive transmission lines. Above all, once installed solar PV systems have relatively low operational and maintenance costs. They require minimal ongoing expenses compared to traditional power plants in areas with abundant sunlight. Since, solar energy is a clean and renewable source, would reduce greenhouse gas emissions. In remote areas, where traditional energy sources may involve diesel generators, solar PV systems can significantly improve air quality and reduce carbon footprint. Additionally, many governments offer incentives, subsidies and tax breaks for solar installations especially in areas with limited access to grid. These incentives can significantly offset the initial costs and make solar energy more financially attractive. Similarly, with advanced thermoelectric material, the figure of merit (ZT value) is improving which elevates coefficient of performance (COP). This will improve efficiency of cooling. The research findings provided valuable information for optimizing thermoelectric cooling systems for various applications involving water cooling.

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