Performance and Economic Evaluation of Solar Photovoltaic Powered Cooling System for Potato Storage

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ABSTRACT

This paper presents the design, fabrication and economic evaluation of solar photovoltaic (SPV) powered vapour compression refrigeration system to attain favourable conditions for potato storage under different operating conditions. The system is consisted of PV panel (490 W), lead-acid battery, 1 kW inverter and 0.18 TR (tonnes refrigeration) vapour compression system. The 2.50 m^3 cold storage structure was constructed and insulated with proper materials. An evaporatively cooled storage structure (1.0 m^3) was used for curing process. The cured potato cultivar (Kufri Chandermukhi) was stored for 5 months. The power output of the panel was measured under no-load, on-load, with and without recirculation of air inside cold store. The average daily SPV energy output and energy consumption by the load were 5.65 and 4.115 kWh, respectively, under full load. It was found that the output power was oversized the load demanded by the cooling system on full load by an average of 26.53%. The obtained results indicated that, the average daily actual COP for loaded and air circulated cold storage structure was 3.25. The average temperature and relative humidity maintained inside the loaded and air circulated storage structure were 283.13 K and 86 %, respectively The total cost of curing and storing 1.0 kg of potatoes inside 2.5 m^3 cold store operated by subsidized PV system, considering the weight loss of potatoes at 6%, would be Rs. 9.02 (1US $ = 46 Rs). While the total cost for the same system operated by grid electricity (Rs. 3.5/kWh) and petrol-kerosene generator (Rs. 10.47/kWh) would be 7.66 and 14.63 Rs./kg, respectively.

Keywords: Solar photovoltaic, performance, cooling load, potato storage, costs, Egypt.

1. INTRODUCTION

With the economic development, the demand of energy is increasing in almost every sector. Most of the power plants consume fossil fuels such as coal, petroleum LPG and electricity etc. for power generation, contributing adversely to quality of environment. Electrical energy is considered a most convenient form of energy sources in rural and urban areas. Providing essential energy needs to the rural areas has been difficult and costly. Until the late 70's, oil was the most used source of energy, which in many cases, had to be imported at a cost, which represented over 50% of these countries foreign exchange earnings. Therefore, governments now realize the importance of establishing reliable and comprehensive energy polices which take into consideration utilization of local sources of energy such as wind and photovoltaic. In spite of best efforts of Government in according high priority to supply of electricity to the villages for farm operations, there is an acute shortage of electricity in rural areas particularly in remote villages. The demand and supply gap is widening with the passage of time.

The increasing shortage of fuel and the high cost of transmission of electrical power have motivated many countries to explore the possibilities of using alternate and renewable sources of energy in agriculture (Bhattacharya, 1991).

The need for refrigeration and air conditioning has long been recognized, and many systems have been developed commercially to provide them, the most commonly used being the vapour compression system. Vapour compression refrigeration systems require mechanical power for driving the compressor, which is usually provided electrically. In areas where electrical energy is available, this refrigeration system is very adequate to satisfy most refrigeration requirements (Eltawil et al., 2006). There are several areas, however, where grid electricity is not available at the moment and is unlikely to be available in the next few decades due to the huge financial outlays involved. These include villages, rural areas and remote locations in developing countries.

The solar photovoltaic (SPV) technology offers tremendous potential of harnessing a portion of solar energy due to its inherent advantages such as easy and silent conversion into electricity using solar cells. It is important to develop SPV and make large-scale applications for control of carbon dioxide (Co_2) emission, supplying high-quality energy to rural off-grid areas and finally as a source of clean energy, when fossil fuels are exhausted. However, for large-scale use, it is necessary to bring down the cost of the SPV electricity significantly. India has made a considerable progress in the development of SPV system during last two decades.

Cold stored (at 275-277 K) potatoes become sweet due to accumulation of sugars and are not suitable for processing and table purposes. The ideal temperature for storing potatoes for processing (chips) and table purposes is 283-286 K. While seed potatoes are require to be stored at 275-277 K. In addition to considerable savings on energy, this type of arrangement would benefit the farmers by reduced storage costs and industries by assured supply of processable potatoes round the year. Most horticultural crops consist of 80 per cent or more water and water loss should be minimizing during storage. The relative humidity should be maintained at about 85- 90% (ASHRAE, 1998).

The study was planned in the following sequential manner.

-Installation of solar photovoltaic panel, and evaluate its performance.

-Fabrication of an experimental storage structure of about 2.50 m^3 capacity.

-Design, fabrication and evaluation of an experimental unit representing the vapour compression cooling.

-Economic evaluation of stand alone SPV powered cold storage plant.

2. MATERIALS AND METHODS

2.1 Experimental Site

The experiments were carried out in the premises of Energy Lab, Division of Agricultural Engineering at Indian Agricultural Research Institute, New Delhi during 2001-2002, which lies at latitude 28.63°N and longitude 77.2°E.

2.2. Installation of Solar Photovoltaic Panel.

To size the PV array and the battery capacity, the average load energy, E_{cons}, and the ampere-hour required per day, Ah_r, should be estimated from the load profile ($Ah_r = E_{cons}$ /system voltage).

2.2.1. PV Array Sizing and Assembly:

The experimental set up consisted of a solar photovoltaic panel, battery, inerter, storage structure and cooling system is fabricated, assembled and installed in the Energy Lab of Division of Agril. Engg, IARI-New Delhi. Plates 1 and 2 show experimental cold storage structure setup powered by SPV.

Plate 1. Arrangement and connections of solar photovoltaic panel, energy storage (batteries) and power conditioning system.

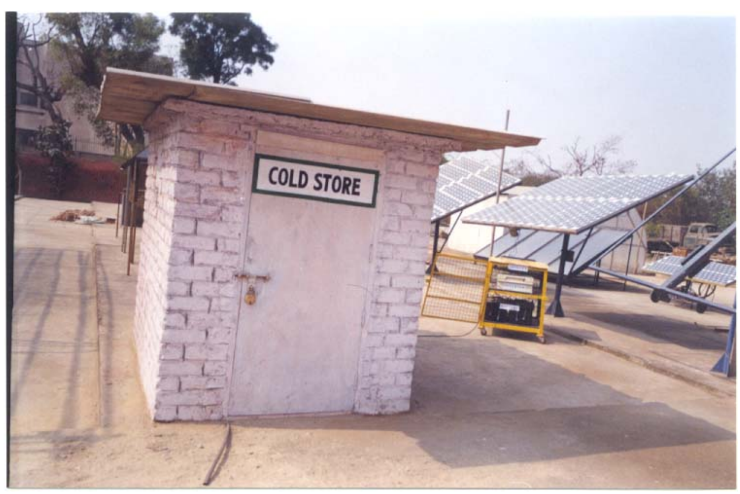

Plate 2. Solar photovoltaic powered cooling system for potato storage.

Design of SPV powered cooling system requires considerable information such as feasibility of certain system within the limiting factors namely physical realization, economic worth, financial feasibility, etc. In addition, one has to consider factors such as materials, components and their optimum combination, components and their design steps, besides its adaptability by customers.

In order to install a PV system at a given site for a required load, the proper array sizing is required. The sizing of various components of the PV system should be done in such a way that the utility factor should remain as close to 1.0.

To size the PV array and the battery capacity, the average load energy, E_{cons}, and the ampere-hour required per day, Ah_r, should be estimated from the load profile (Ah_r required per day = E_{cons} /system voltage).

The theoretical daily expected energy output of the PV array in Wh could be expressed by the equation:

$$P_{th.output} = (n \text{ X } A \text{ X } S_{Ins} \text{ X } \eta_{mod}) \qquad (1)$$

where: n = the number of PV modules,

A = the module area, m^2,

S_{Ins} = the total insolation, $Wh/m^2/d$,

η_{mod} = the overall module efficiency experimentally determined under actual field operating conditions, %, and

In order to determine the annual energy output from the PV system, the knowledge of annual peak energy output at the site is not enough. Chander et al. (1988) noticed that, taking peak rated power for estimating the annual energy output from solar panel (array) would result into slightly higher values than the experimental ones achievable under the same global insolation and temperature. Therefore, instead of using the peak rated power of the modules at standard operating conditions, the following equations was used for the power (P_{output}) and temperature (Fuentes and Fernandez, 1984):

$$P_{output} = A_0 + A_1 S_{Ins.} + A_2 T_p + A_3 S_{Ins} T_p \qquad (2)$$

and

$$T_p = T_o + B_1 S_{Ins} + B_2 WV \qquad (3)$$

Where: T_p = the module temperature, K, S_{Ins} = the insolation, W/m^2,

T_o = the ambient temperature, K, and WV = the wind velocity, m/s.

The coefficients of these equations are determined by multiple regression technique with the help from several days' experimental data. From these equations, the power output from the modules can be estimated with better accuracy. In case of large array of PV modules, the power output is given by:

$$P_{array} = \eta_{array} S_{Ins} A_{array} PF \qquad (4)$$

Where: P_{array} = the array power output, W,

η_{array} = the array efficiency, %,

S_{Ins} = the insolation on a tilted surface, W/m^2,

A_{array} = array area, m^2 and

PF = module packing factor = area of module/area of array.

In order to obtain the useful AC energy output from a stand-alone PV system, the PCS efficiency, utility factor (the ratio of utilized energy to that of generated energy) and storage efficiency should also be taken into account. The losses due to module mismatch, cable and shadowing should be minimized.

In order to supply the required power, the arrays should be capable of producing sufficient current and voltage to run the applications, and it can be connected in series and in parallel to obtain the desired voltage and current, respectively (Smith, 1976).

The system consisted of PV panel consisting of 14 modules (1.02 m length x 0.41 m width, M/S Udhaya Semi-conductors, Ltd., Coimbatore) which were installed and fixed on a rectangular metal frame and mounted on a proper inclined angle of 30º from the horizontal plane.. The modules were fixed at 4 m distance from the cold store structure. The panel faced towards south with manually operated two-axis orientation facility (inclined towards East from 8.00 hrs to 12.00 hrs and facing South from 12.00 to 14.00 hrs, and thereafter towards West up to 18.00 hrs.). Every module had 36 circular cells of 10 cm diameter. Cells were connected in series in each module to provide 35 Watt peak power under designed operating conditions. The circuit output voltage of each module at the point of peak power output is about 21 V and short circuit current is about 2.30 A. The above values are specified at the standard test conditions (1000 W/m^2 solar radiation at 298.16 K cell operating temperature and an air mass, AM, of 1.5). Under field conditions, the output power is normally less than the rated peak power.

The solar generator consisting of 14 PV modules was divided to two sets. Each seven modules were connected in parallel forming two main branch circuits each having an open circuit voltage of about 18 V, and connected in series (Figure 1).

2.2.2. Battery, Wire Sizing and Inverter

The most commonly used storage battery for PV applications is the lead-acid type. Battery life is directly related to how deep the battery is cycled each time. The battery charge-discharge efficiency is assumed to be 0.80 and nominal system voltage to be 24 V DC.

The Watt-hour capacity, B_W, and ampere-hour capacity, B_A, of a battery are determined by predefined days without insolation back up as follows (Buping et al., 1995):

$$B_W = k_b \times D \times E_{cons} \quad (5)$$

$$B_A = B_W / V_B \quad (6)$$

Where: B_W = the Watt-hour capacity of the battery, kWh,

B_A = the ampere-hour capacity of the battery, Ah,

D = the days without insolation,

E_{cons} = the daily consumed electric energy in the load, kWh/d,

V_B = the voltage of battery, V and

k_b = the correction factor decided by battery efficiency, η_B, discharge depth and effect of environmental temperature etc. A value between 2.0 and 2.5 (average 2.25) is usually adopted.

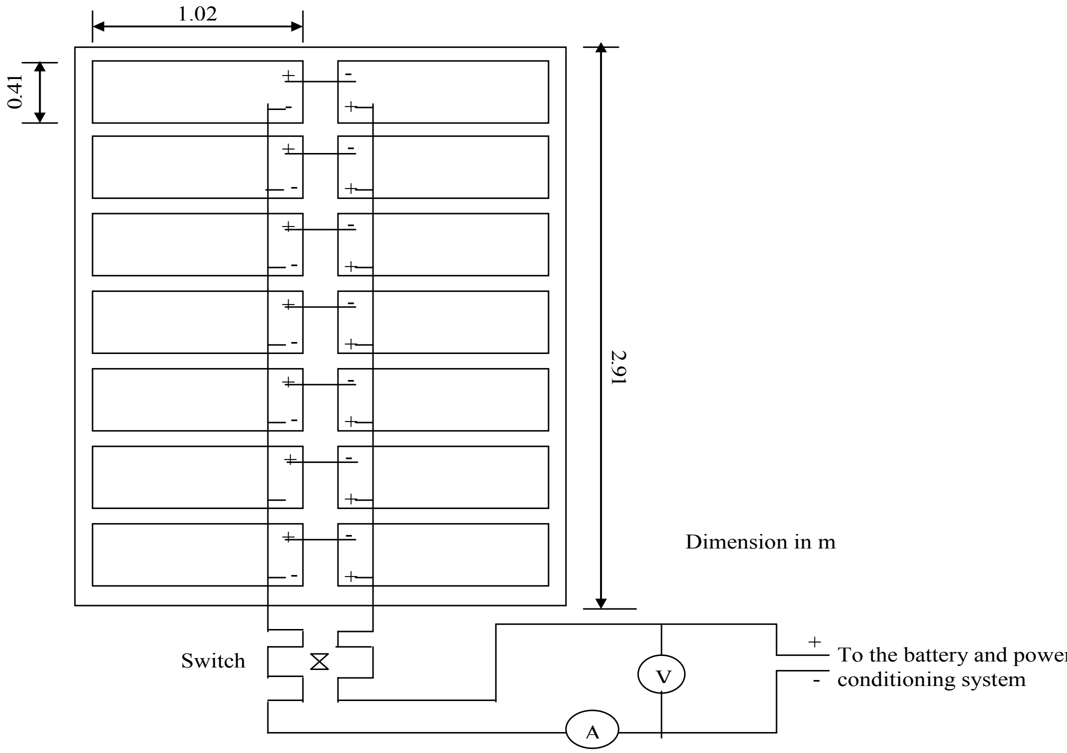

Figure 1. System circuit diagram and wiring connections of modules in arrays.

Two black gold lead-acid deep-cycle batteries of 2.160 kWh capacity each were used for storage of power generated by the PV array during day time to meet load requirements at night time. The batteries were charged fully before starting the experiments. The distance between the battery and the power conditioning system (inverter) was made as short as possible. The positive and negative terminals of the battery were connected to the respective terminals of the inverter using a 50 mm^2 plaza R cables 1100 volts. This wire is sufficient to keep the voltage loss of the PV panel and battery less than 0.5% at the mentioned distance.

An inverter of Mos 24 V, 1250 VA Mfd. By Bitek Electronics (P) LTD was used. The power conditioning system (PCS) efficiency assumed to be about 85%.

2.3 Cold Store Design and Construction

The design of cold storage facilities is usually directed to provide for the storage of perishable commodities at selected temperature with consideration being given to a proper balance between initial, operating, maintenance, and depreciation costs.

Hence poor insulation of the store results in extra energy consumption for cooling the potatoes and in additional capital costs for the necessary cooling equipment.

2.3.1 Construction of Storage Structure

Based on design considerations (Eltawil, 2003) the storage structure was constructed with the following specifications:

-Outside dimension of about 2.11 m length x 1.585 m width x 1.80 m height.

-Inside dimensions of about 1.68 m x 0.901 m x 1.65 m.

-Rectangular shape and East-West orientation.

-White surface walls.

- Insulation: Fiberglass (glass wool) was attached to the walls, door, windows and ceiling (roof), because it is light in weight, low in cost, non-hygroscopic and has high strength. Also, a vertical air space between walls is provided because still air has low thermal conductivity.

-Dark condition was maintained in the cold store (without diffused light) to avoid greening of potato tuber.

The construction details of walls, door, windows and ceiling are presented in Figures 2, 3 and 4 (Eltawil and Samuel, 2007). The floor consisted of 0.10 m lightweight concrete (k= 1.1 W/m.K) installed over well-compacted gravel, which can take the load of stored commodity. The floor was covered from upper surface with 5 cm hard wooden sheets.

The axial-flow exhaust fan attached with regulator was mounted on the south wall to draw air through the window located on the opposite wall to control relative humidity, and reduce concentration of carbon dioxide released by stored produce inside the storage structure. The fan has blade diameter 225 mm, 220/240 AC, 50 Hz 1 phase, and 1400 rpm. The outlet of exhaust fan was closed with window having the same specification as of the opposite window when the fan is off.

Where the recirculation fan is located after the evaporator coil, the heating effect imparted to the air by the fan will reduce the relative humidity of the air, which should have been at saturation point as it left the cooling coils. The axial-flow fan was hanged under the ceiling and has the same specification as of the exhaust fan.

The 0.830 cu-m storage bin was made from 2-inch (5.08 cm) steel, and side walls were made by welded wire mesh. The air spaces between the storage bin and main structure were provided to improve recirculation of air and to avoid moisture condensation on the stored commodity.

2.4 Estimation of Cooling Loads of a Cold Storage Building for Potatoes

The refrigeration load for potato store is made up of six basic components (Bishop et al, 1980; Rastovski, 1987; ASHRAE, 1998; Prasad1999 and Arora, 2000) as follows:

i) Sensible heat gain through walls, floor, and roof.

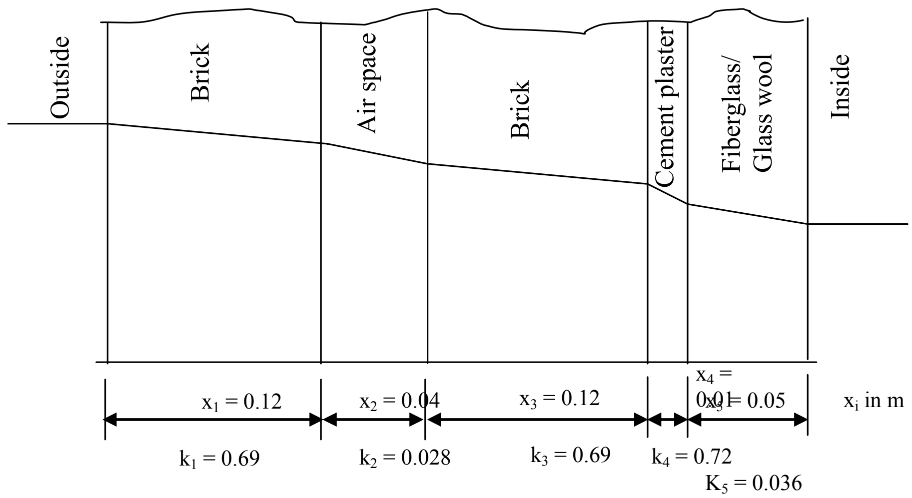

Figure 2. Construction of wall.

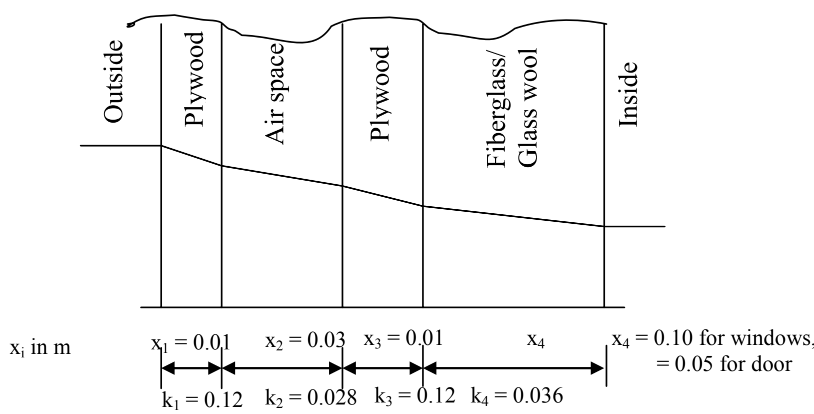

Figure 3. Construction of windows and door.

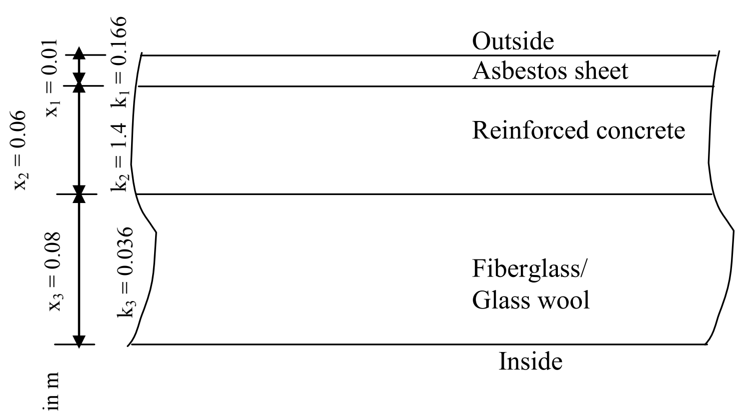

Figure 4. Construction of ceiling (roof).

Thermal properties of materials used for construction, allowance for sun effect and physical properties of potatoes are given in Tables 1, 2 and 3.

Total heat gain through walls, ceiling and floor (Q_1) = $q_{T\ walls} + q_{T\ ceiling} + q_{T\ floor}$ (7)

= 54.718 + 15.241 + 44.097= 114.056 W

ii) Heat removed to cool potatoes (550 kg) from the initial temperature to some lower temperature (Q_2)= 346.615 W

iii) The heat produced by respiration of potatoes (Q_3) = 2071396.8 J/d = 23.975 W

iv) Heat produced by fans (Q_4) = 40.833 W

v) Heat supplied by air renewal (Q_5) = 203.2 kJ/d = 2.35185 W

vi) Heat produced by equipment-related load (Q_6) = $0.05\ to\ 0.1\sum_{i=1}^{i=5} Q_i$ (8)

= 52.783 W

Cooling capacity (Q_c) = 1.2 X Q_{total} = 696.732 W = 9.98 kcal/min
= 0.180 TR (tonne refrigeration).

Table 1. Thermal properties of materials used in the construction.

Substance	Thermal conductivity, k (W/m.K)	References
Air space	0.028	ASHRAE, 1997
Asbestos sheet	0.166	Geankoplis, 1997 and Arora & Domkundwar, 1999
Bricks	0.69	Geankoplis, 1997 and Arora & Domkundwar, 1999
Cement plaster	0.72	Albright, 1990 & ASHRAE, 1997
Concrete	1.40	ASHRAE, 1997
Fiberglass/Glass wool	0.036	ASHRAE, 1997
Hard wood	0.158	Arora, 2000
Lightweight aggregate concretes	1.10	ASHRAE, 1997
Plywood	0.12	ASHRAE, 1997

Table 2. Allowance for sun effect (ASHRAE, 1998).

Typical surface types	East wall, K	South wall, K	West wall, K	Flat roof, K
Light colored surfaces White stone, Light colored cement and white paint	3	2	3	5

Table 3. Thermo-physical properties of potato used in the experiment.

Property	Unit	Value	Remarks/References
Specific gravity	-	1.08	Measured
Specific heat	kJ/kg K	3.630	ASHRAE, 1998
Thermal conductivity	W/m K	0.55	Buhri and Singh, 1993
Heat of respiration	mW/kg	19.7- 47.0	Sastry et al., 1978
Transpiration coefficient	ng/kg s Pa	25	Sastry et al., 1978

When the potatoes have been cooled to the required storage temperature, part of the cooling requirement- viz, Q_2- is no longer necessary. Less cooling is then needed to maintain the required temperature in the store and the cooling system can operate for a shorter period or the cooling capacity can be reduced. The equipment is selected on the basis that all of the maximum load will occur at the same time to ensure that the design temperature will never be exceeded.

2.4.1 Design of Cooling System

Refrigeration is the science of providing and maintaining temperature below that of surrounding atmosphere. Vapour compression system is commonly used in mechanical refrigeration to achieve the lower temperatures, and it is described by many authors (Prasad, 1999; Arora, 2000 and Kulshrestha, 2001).

The actual Vapour compression system consists of an oil separator, a receiver and a drier-cum-filter besides the main components: a compressor, a condenser, an expansion device and an evaporator (Figure 1). The specification of vapour compression cooling system used in the experimentation is given in Table 4.

2.5 Measurements

Performance evaluation of solar panel was planned as first step for evaluation of a solar PV powered cooling system. The power output of the panel was measured for different solar radiations and module combinations. The following electrical parameters were measured under no-load, on load of the cooling system, with and without storage of potato, and with and without circulation of air inside cold storage structure: Open circuit voltage (V_{oc}) and Load voltage (V_L) were measured with the help of Fluke 73 series multimeter while short circuit current (I_{sc}) and Load current, (I_L) were measured with the help of Ammeter (0-15 A) connected in series with the circuit. The energy consumption in kWh was measured with the help of energy meter.

Table 4. Vapour compression cooling system.

Item	Specifications
Drier	Silica gel
Compressor	-Reciprocating sealed compressor AE7 ZA7, -1/6 HP, 230 V- 1.4 A, 50Hz-IP-LRA-9-R12 -Suction pressure is 33.096 kN/m^2 -Discharge pressure is 1241.1 kN/m^2
Condenser	-Consisted of 24 tubes, 0.30 mm thickness and 6.0 mm diameter each -Total length of the tube is about 17.90 m and its area is 0.3374 m^2, and it is divided into two parts (18 main tubes + 6 secondary tubes) to increase the exposed area, and to increase the heat transfer to the ambient air. -It was kept at 0.10 m from the West wall -The ambient airflow was used to cool the condenser, therefore, the condenser set in the windward direction.
Evaporator	- Copper tubes of 10 mm diameter - Area of the tube is about 0.2230 m^2 - Total length of the evaporator tube is about 7.10 m - The tubes are arranged on rectangular shaped box which has a circumstance of about 1.25 m each and - Number of evaporator tubes is 6
Chiller	The amount of moisture from the air condenses on the evaporator surface was collected by chiller (tray) kept under the evaporator fabricated for that purpose.
Refrigerant	Freon-12 (250 ml) was used to serve as refrigerant for low, medium and high temperatures
Expansion device	A capillary tube of 0.003 m diameter and 2.0 m length was used and kept in contact with the suction tube (evaporator exit tube) to sub-cool the condensate.
Thermostat	Mechanical thermostat was used

The following parameters were identified for performance evaluation of a solar powered cooling system.

Insolation (S_{Ins}) for clear sunny days was measured by thermoelectric pyranometer, which was set in the same plane as the solar panel for instantaneous insolation measurements; *ambient temperature* (T_o) and *ambient relative humidity* (r.h.$_o$) were measured under shade to avoid the effect of direct solar radiation by using digital sensor, and *wind velocity* (WV) and *ventilation rate* was measured by using Vane type anemometer.

Temperatures for cooling system and PV panel (T_p) were measured with the help of an iron-constantan thermocouples and digital temperature indicators. All the thermocouples were checked for their calibration at the freezing and boiling points of water. The temperatures for compressor suction, T_1, and delivery, T_2; condenser, T_3; evaporator, T_4, and at 3 centered locations of cold storage structure, at bottom, T_5, center, T_6, and the top-under the ceiling, T_7 and on side walls, North, T_8, East, T_9, South, T_{10}, and West, T_{11} were recorded at one hour interval.

The average relative humidity inside vapour compression cold storage structures, r.h.$_{incs}$, was measured at an interval of one hour with the help of digital r.h. indicator, type Humitherm-842C.

2.6 PV Array Performance Characteristics

The performance of a PV array was measured in terms of its conversion efficiency. The voltages and currents as well as the observations mentioned above which produced by one module and different configurations of PV modules at different times of the day were measured for different position of the panel. Two modules connected in series string, which give the open circuit voltage of about 37 V and under load (cooling system) reduced to about 24 V (input voltage to power conditioning system). Different parallel combinations of these series connection were also evaluated.

As conversion efficiency of array is influenced by panel temperature, the temperature of the panel was measured with help of thermocouples fixed at the backside of the array. Power output (P_{output}) of the array was determined by multiplying the current into voltage.

$$P_{output} = V_{OC} * I_{SC}, \quad \text{W} \tag{9}$$

And the maximum power P_{max} provided by the device at a point on the characteristics, where the product IV is the maximum.

Thus
$$P_{max} = I_{max} * V_{max} \tag{10}$$

$$\text{Fill factor } (FF) = P_{max} / V_{OC} * I_{SC} \tag{11}$$

The FF value in Si is about 0.67. The maximum possible output can be given as:

$$P_{max} = V_{OC} * I_{SC} * FF \tag{12}$$

The conversion efficiency was computed as the ratio of maximum output power delivered by the PV module to the total incoming solar power at a given cell temperature.

$$\eta = \frac{P_{max}}{P_{in}} = \frac{V_{OC} * I_{SC} * FF}{Incident\,solar\,radiation * area\,of\,solar\,cell} * 100, \quad \% \tag{13}$$

The area in this calculation is the entire frontal area of the cell or modules.

2.6.1 Oversizing Calculation

Oversizing is defined as the deviation of the load energy consumption and the stored energy from the expected energy output of the PV array per day. Oversizing can be calculated using the following relation (Taha, 1995).

$$Z = \frac{P_{output} - E_{cons}}{P_{output}} x100 \qquad (14)$$

where: Z = oversizing, %,

E_{cons} = the measured total energy consumed by the load, kWh/d and

P_{output} = the expected energy output of the module in kWh/d

2.6.2 Performance of Vapour Compression Cooling

The PV solar refrigerator was operated for about 48 h, till temperature in the cold store was stabilized. The system performance was evaluated without and with load (storage commodity), where the following observations were recorded at hourly interval for 24 h.

The coefficient of performance of a vapour compression cooling cycle, COP, is expressed as:

COP = Energy removed at the evaporator/ Energy supplied at the compressor

= Refrigeration effect/ Energy input (15)

The maximum possible COP is that of a Carnot cycle, and is given as:

$$COP_{Carnot} = \frac{T_{evap}}{T_{cond} - T_{evap}} \qquad (16)$$

Where: T_{evap} = evaporator temperature, and T_{cond} = condenser temperature.

COP_{real} = 75-85% (average 80%) that of COP_{Carnot}.

And the cooling efficiency, $\eta_{cooling} = \frac{COP_{real}}{COP_{Carnot}} x100$, % (17)

2.7 Unit Cost of Electricity

The unit cost of electricity, UCE_{PV}, produced by a PV system can be calculated as:

$$UCE_{PV} = \frac{Levelized\ annual\ cost\ of\ PV\ system}{Annual\ electricity\ output\ from\ the\ PV\ system} \qquad (18)$$

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 in turn, can be computed as a product of the capital cost, C_o, and the capital recovery factor, CRF, i.e.

$$Annual\ capital\ recovery\ cost = C_o \left[\frac{d\,(1+d)^n}{(1+d)^n - 1} \right] \qquad (19)$$

The capital recovery factor for fuel, CRF_f, can be calculated with the following formula (ASHRAE, 1999):

$$CRF_f = \frac{(d - i_f)/(1 + i_f)}{1 - \left[1 + \frac{(d - i_f)}{(1 + i_f)}\right]^{-n}} \qquad (20)$$

where:

C_o = capital cost, n = expected useful life,

d = discount rate or attractive rate of return and i_f = fuel inflation rate.

In the present analysis it is assumed that:

(i) Discount rate is 10%.

(ii) Cost of SPV module was considered with and without subsidies, while there is no subsidy provided with petrol-kerosene generator.

(iii) The useful life of the PV modules and petrol-kerosene generator are 20 and 5 years, respectively. The service life of the petrol-kerosene set may vary substantially, depending on maintenance, make, etc.

(iv) Storage batteries generally have a much shorter life span (3 years) than the PV array and will have to be replaced a number of times during the life of the system.

(v) Electricity from petrol-kerosene generator is available round the clock (full time running).

(vi) Taxes and insurance costs are not to be paid.

(vii) The average SPV and petrol generator energy output are 4.50 and 19.44 kWh/d. In case of petrol generator there is an excess energy, which can be used for lightning or for large scale cooling system.

2.7.1 Economic Considerations for 2.5 m^3 Cold Storage Structure

The cost economics for the 2.50 m^3 storage structure have been calculated for storage of horticultural produce under the following assumption.

a. The structure is used for storage of 550 kg of potato.
b. The produce is stored for a period of 150 days i.e., from the beginning of April till the end of August (It can be used year round for other horticultural produce).
c. The total initial investment being small is met from the farmer's own resources.
d. The cold storage structure has been placed on the farmer's own premises and no rent is paid for the space.
e. No insurance and taxes are involved in the cold storage structure.
f. The colour paint and plastic sheet would be replaced every 5 years.
g. The farmer (storekeeper) makes the arrangement of periodic ventilation of structure and check up the stored produce.
h. Dark condition was maintained inside the cold storage structure.

2.7.2 Economic Considerations for Cooling System (0.180 Tonne Refrigeration)

The cost economics for the vapour compression cooling system attached to the 2.5 m^3 storage structure (550 kg potatoes) have been calculated under the following assumption.

a. The cooling load of loaded and air circulated storage structure is 696.273 W (0.180 TR).
b. The average daily energy consumption by the cooling system for loaded and air circulated storage structure is 4.115 kWh/d.

c. The running period of the cooling system is 150 days, i.e. from the beginning of April till the end of August (It can be used year round for other horticultural produce).
d. The ambient air is used to cool the condenser.
e. The initial investment being small is met from the farmer's own resources.
f. No insurance and taxes are involved in the cooling system.
g. The thermostat and spare parts would be replaced every 5 years.
h. The farmer (storekeeper) makes the arrangement for inspection and maintenance of power sources (PV and battery) and checking the cooling performance.

3. RESULTS AND DISCUSSION

3.1 Effect of Insolation on the Panel (Module) Performance

To study the effect of insolation on the module performance The position of the solar panel was adjusted two times in a day as it was pointed out by many authors (Baltas et al., 1986; Chander et al., 1988 and Ramamurthy et al., 1992) that the energy output from the dual axis tracking system is higher as compared to the fixed PV system. The recorded data indicated that the insolation, S_{Ins}, was low in the morning and rose up to 11.00 h and thereafter slightly reduced as it approached 12.00 h. After the adjustment of the solar panel angle it again rose to a peak value at 13.00 h and thereafter decreased to a lower value (Figures 5 and 6). The sudden down ward tilt at 12.00 and 14.00 h may be the result of changing the orientation of the panel at this time. Lower values of insolation, S_{Ins}, at 12.00 h indicated that the sun rays fall at an angle. However, when the panel faced southward the sun rays were perpendicular to the array, resulting in increased insolation values, which peaked at 13.00 h. The S_{Ins} results on the panel surface are compatible with those observed by Hailu (1999).

The average daily S_{Ins} measured on the module surface for different clear sunny days were 5.53, 6.33 and 3.33 kWh/m^2/d during summer 2001, 2002 and winter 2002, respectively. The average maximum insolation, 862.86, 960.55 and 671.33 W/m^2 were recorded at 13.00 h during summer 2001, 2002 and winter 2002, respectively. Also, the recorded data from the field study indicated that, the higher S_{Ins} were observed before noon in comparison to those in the after noon (Figures 5 and 6).

The analysis of recorded data indicated that, the power output of solar module changed significantly with S_{Ins} during summer seasons, while it changed highly significantly during winter season which may be due to increase of clearness index. The average maximum P_{output} of 36.72, 37.19 and 34.51 W were recorded at 13.00 h during summer 2001, 2002 and winter 2002, respectively. The reason for that may be due to; the generated I_{sc} was increased more than the drop in voltage at noon.

The average daily energy output of 0.289, 0.296 and 0.245 kWh/d with standard deviation of 5.12, 4.31 and 6.74 were recorded during summer 2001, 2002 and winter 2002, respectively. Also, the higher P_{output} at mornings was observed in comparison to those in the evenings, this may be due to the module heating up in the after noon more than mornings. In addition to, the higher S_{Ins} at mornings in comparison to those in the after noon.

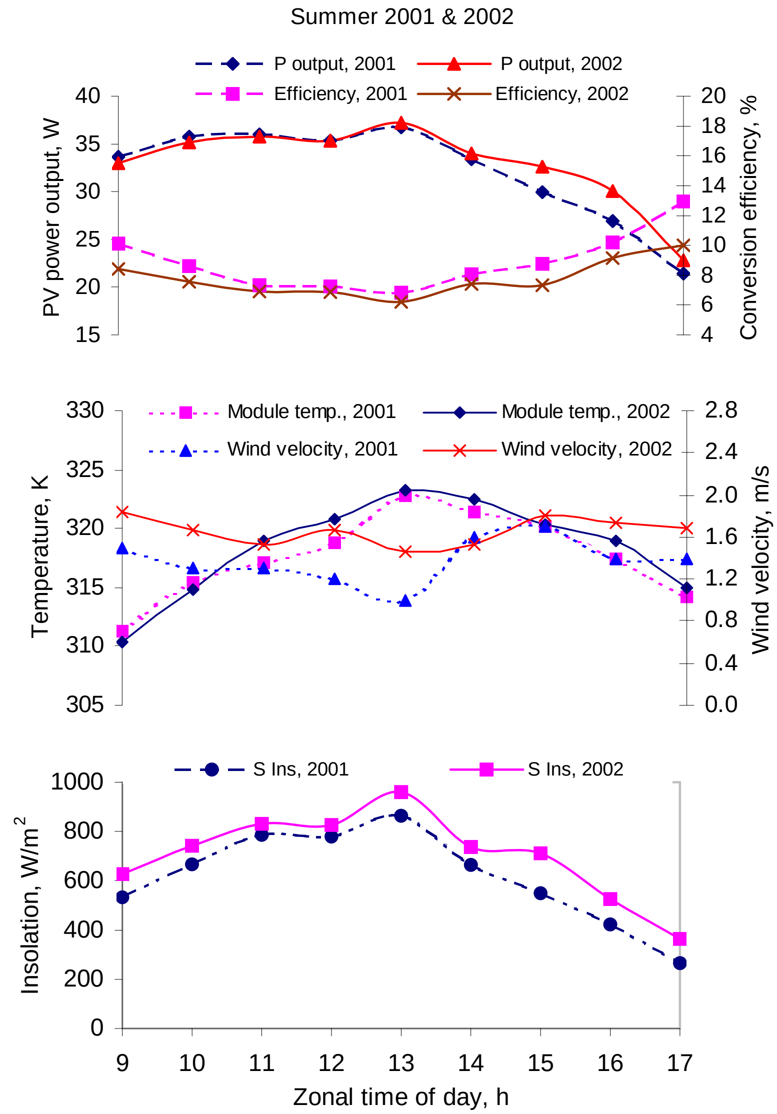

Figure 5. Variation of solar module power input, output and its conversion efficiency for typical clear sunny days during summer seasons 2001-2002.

Analysis of the recorded data indicated that, the V_{oc} changed significantly with ambient temperature, T_o, which indirectly affected the module/panel temperature. Also, the analysis indicated that, the solar module output in respect of V_{oc} did not change significantly with S_{Ins} on clear days, this may be due to the fact that, the PV module output did not increase beyond a certain limit of photons equivalent to energy gap (Green, 1982 and Shaltout et al., 1995). The maximum open circuit voltages were observed on the mornings when the module temperature was lower; this is in agreement with that observed by Onyegegbu (1989).

The declination of V_{oc} is according to the increase in temperature of solar module. On clear days, the short circuit current is linearly proportional to S_{Ins}, though it was observed that the same insolation level on different days did not produce the same short circuit current. The short circuit

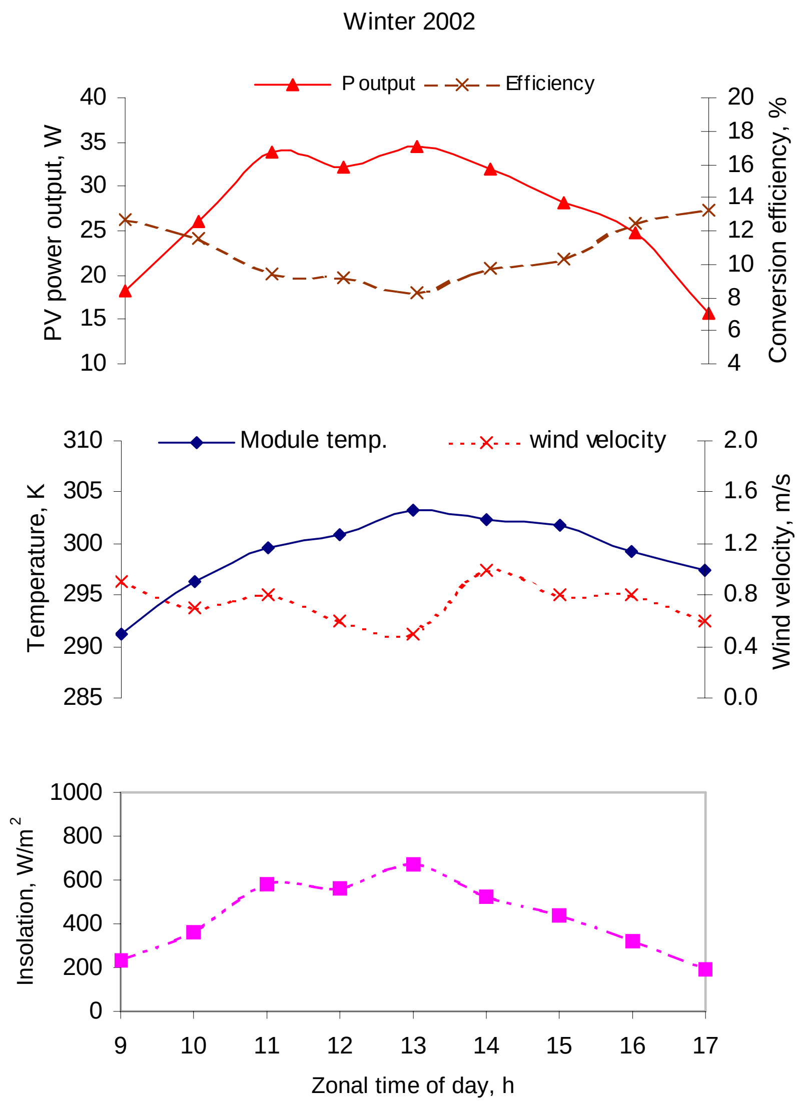

Figure 6. Variation of solar module power input, output and its conversion efficiency for typical clear sunny days during winter 2002.

current, I_{sc}, increases with increasing insolation intensity due to the increase in the number of photons generating the photo current, in addition to the perceptible improvement in I_{sc} with increase in temperature, which is the consequence of improvement in the diffusion lengths and due to the shift of the absorption edge to lower energies (Shaltout et al., 1995).

It was found that, increasing the cell (module) temperature causes a rise in short circuit current. This increase in cell temperature would arise due to high insolation heating, low wind velocity with the consequent low heat transfer from the cell to the ambient and a high ambient temperature. For this reason, maximum open circuit voltages were observed in the mornings when the cells have not yet been heated up. The higher I_{sc} and lower V_{oc} were measured during summer seasons in comparison to those in the winter; this may be attributed to the high insolation heating in summer. The higher cell/module temperature, T_p, causes a reduction of peak power. The V_{oc} was significantly decreased with increase in T_p, while I_{sc} increased slightly as temperature increased. This result was in agreement with Ramamurthy et al. (1992).

The hourly variation of conversion efficiency, η_{mod}, is illustrated in Figures 5 and 6. It is clear that the efficiency is relatively higher during the early and late hours of the day as compared to midday as a result of thermal effects. On clear sunny days, it was found that, the conversion efficiency is inversely proportional to the module temperature. As can be seen from the recorded data, the efficiency drops during the summer seasons as compared to winter because of the higher ambient temperature and insolation available, which in turn caused the higher module temperature and hence relatively lower performance. This is in agreement with observation made by Kalogirou (2001).

The average daily η_{mod} of 8.90, 7.77 and 10.74% with standard deviation of 1.94, 1.21 and 1.76 corresponding to T_p of 317.7, 318.3 and 299.1 K were recorded for clear sunny days during summer 2001, 2002 and winter 2002, respectively. These results are in agreement with that pointed out by Green (1982) and Singhal and Singh (1997). The results showed that, the conversion efficiency decreased with the increase of module combinations. The reason for that may be attributed to the fact that increasing module combinations causes an increase in the generated currents, which led to heating up of wires and hence increased losses. Therefore, the low values of conversion efficiency were occurred with combinations of 2 X 6.

Several multiple regression equations were obtained and can be used to predict the module power output, P_{output}, and its efficiency, η_{mod}, the equations are as follows:

a. For Summer,

$$P_{output} = -25.0093 + 0.1542\, S_{Ins} + 0.1407\, T_p - 0.0004\, S_{Ins}\, T_p \qquad R^2 = 0.994 \qquad (21)$$

and

$$\eta_{mod} = 39.0783 - 0.0364\, S_{Ins} - 0.0841\, T_p – 0.0001\, S_{Ins}\, T_p \qquad R^2 = 0.982 \qquad (22)$$

where: $310.30 \le T_p \le 323.30$, K and $365.00 \le S_{Ins} \le 960.55$, W/m^2

b. For Winter,

$$P_{output} = -268.352 + 0.9019\, S_{Ins} + 0.9300\, T_p - 0.0029\, S_{Ins}\, T_p \qquad R^2 = 0.981 \qquad (23)$$

and

$$\eta_{mod} = -5.9040 + 0.04855\, S_{Ins} + 0.0709\, T_p – 0.0002\, S_{Ins}\, T_p \qquad R^2 = 0.982 \qquad (24)$$

where: $291.16 \le T_p \le 303.16$, K and $191.07 \le S_{Ins} \le 671.33$, W/m^2

A multiple regression equations was obtained and can be used to predict the module temperature, T_p, the equation as follows:

a. For Summer,

$$T_p = -3.0995 + 1.0150\, T_o + 0.0123\, S_{Ins} – 0.6973\, WV \qquad R^2 = 0.975 \qquad (25)$$

where: $365.00 \le S_{Ins} \le 960.55$, W/m^2 , $302.80 \le T_o \le 312.12$, K and

$1.5 \leq WV \leq 1.8$, m/s

b. For Winter,

$$T_p = 36.9835 + 0.8864\ T_o + 0.0083\ S_{Ins} - 0.6811\ WV \qquad R^2 = 0.962 \qquad (26)$$

where: $191.07 \leq S_{Ins} \leq 671.33$, W/m^2, $286.64 \leq T_o \leq 295.29$, K and

$0.5 \leq WV \leq 1.0$, m/s

It was found that increasing module combination (number of modules) in the given configuration led to increase in power output due to increase in the generated short circuit current. While, there was a slight increase in the load power with the increase of module combinations. In case of the system working under full load (with stored potatoes and with circulation of air inside cold store) the load power was slightly higher than without stored potatoes, this may be attributed to increase of cooling load accompanied with heat stored in potatoes.

3.2 SPV Stand-Alone Powering Cooling System

From the above discussion, it was found that, combinations 2 x 5 and 2 x 6 can be used to power the cooling system at day time during summer season, but the excess power which can be stored in the battery is not enough to run the system overnight and it required an auxiliary power for few hours specially during clouding days. Therefore it was decided to use 2 x 7 configurations to power the cooling system.

Comparing performance of combination 2 x 6 and 2 x 7 on full load basis is shown in Figures 7 and 8. The average daily load energy of 3.68 and 3.72 kWh/d, which correspond to energy output of 4.83 and 5.60 kWh/d for combinations 2 x 6 and 2 x 7, respectively, were recorded during summer 2001, under full load. The average daily open circuit voltages and currents were 37.28 and 37.36 V, and 9.98 and 11.55 A, respectively, while the average daily load voltages and load currents were 24.24 and 24.38 V, and 11.68 and 11.73 A, respectively, for the same combinations.

The average daily η_{array} of 10.47 and 10.36% with standard deviation of 3.84 and 3.70, respectively, were recorded for the same combinations correspond to average daily S_{Ins} of 7.382 kWh/d, T_p of 317.64 K and WV of 1.25 m/s.

It was found that the output power was oversized the load demanded by the cooling system on full load from about 6.30 A.M. to 5.30 P.M. for configuration 2 x 6, while incase of configuration 2 x 7 the oversizing was from about 6.15 A.M. to 6.00 P.M. The excess power saved to the battery to operate the system overnight.

3.3 Energy Consumption by Cooling System for Loaded Cold Storage Structure

The variation of SPV power output, P_{output}, and energy consumption by the cooling system, $E_{cons,}$ as affected by weather conditions and condenser and evaporator temperatures with respect to zonal time of tested days is shown in Figure 9. The average daily SPV energy output and E_{cons} were5.60 and 4.115 kWh/d, respectively, under full load, while, the corresponding average daily S_{Ins} of 7.382 kWh/m^2/d, T_o of 305.78 K, T_3 of 340.31 K and T_4 of 272.71 K were recorded in tested sunny days during summer 2001.

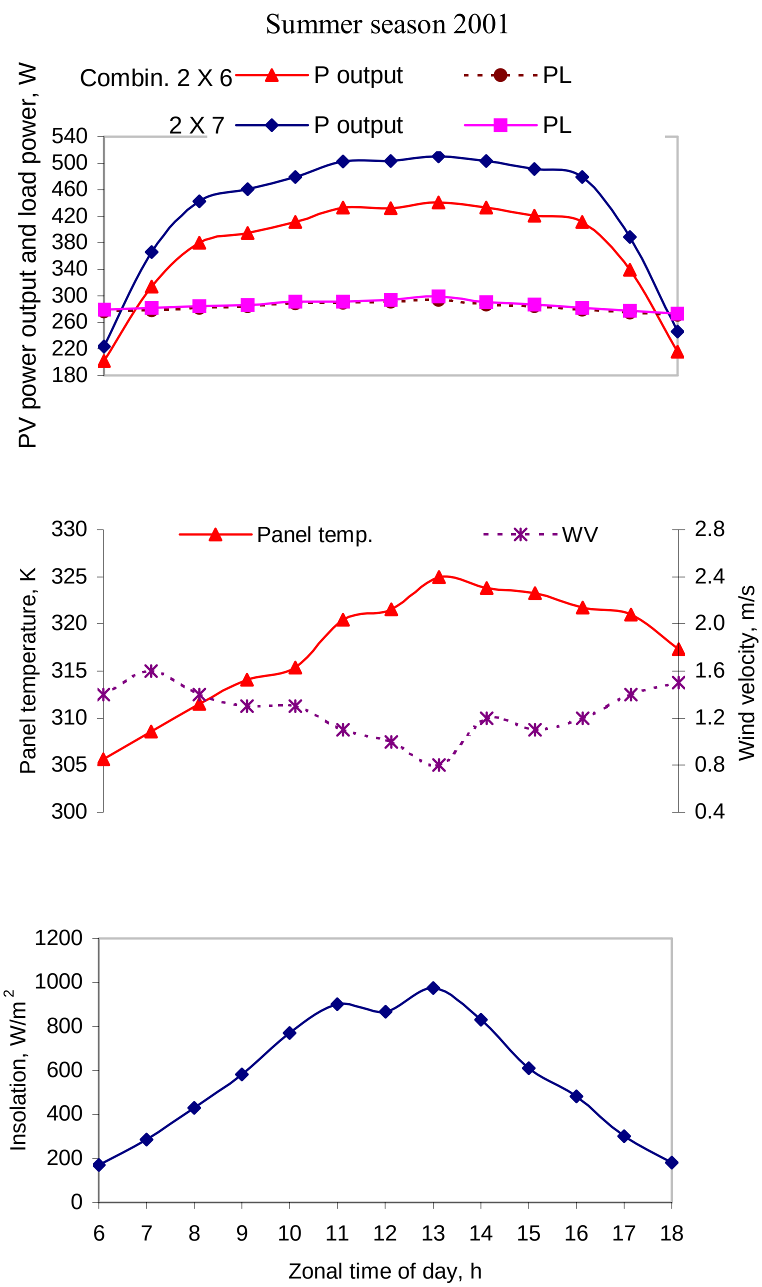

Figure 7. SPV power output and full load power (loaded and air circulated cold store) as affected by weather conditions for combinations 2 X 6 and 2 X 7 for a stand-alone PV during typical clear sunny days in summer 2001.

The recorded data revealed that the difference between condenser and evaporator temperatures under full load is more than that of empty and air circulated cold store. The energy consumption under full load is slightly higher, which may be due to certain amount of heat continuously produced by potatoes and evacuation of this heat consumes more energy. The maximum power

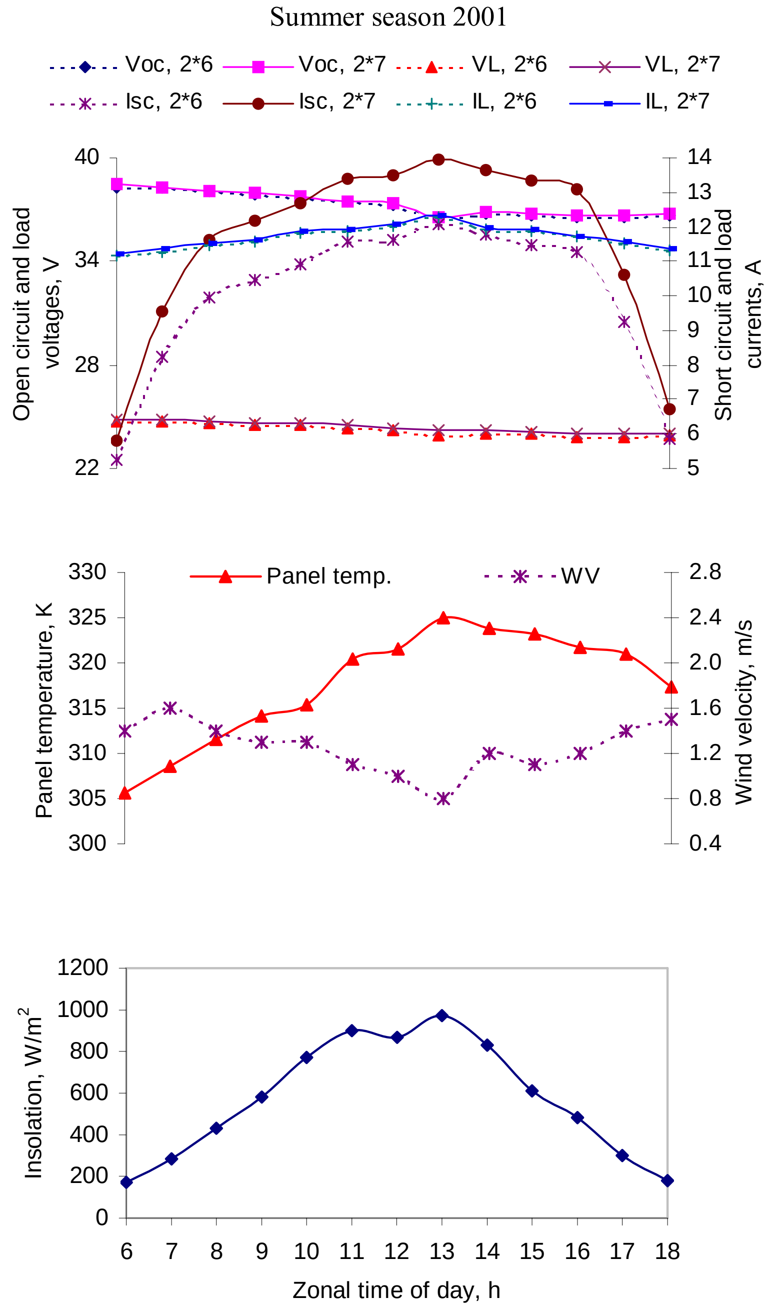

Figure 8. SPV output parameters and on full load (loaded and air circulated cold store) as affected by weather conditions for configurations 2 X 6 and 2 X 7 for a stand-alone PV in typical clear sunny days during summer 2001.

consumption was recorded at noon hours when the difference between condenser and evaporator temperatures was highest.

The correlation between energy consumption (E_{cons}, Wh) by cooling system under full load, and condensation and evaporation temperatures during tested sunny days can be expressed as follow:

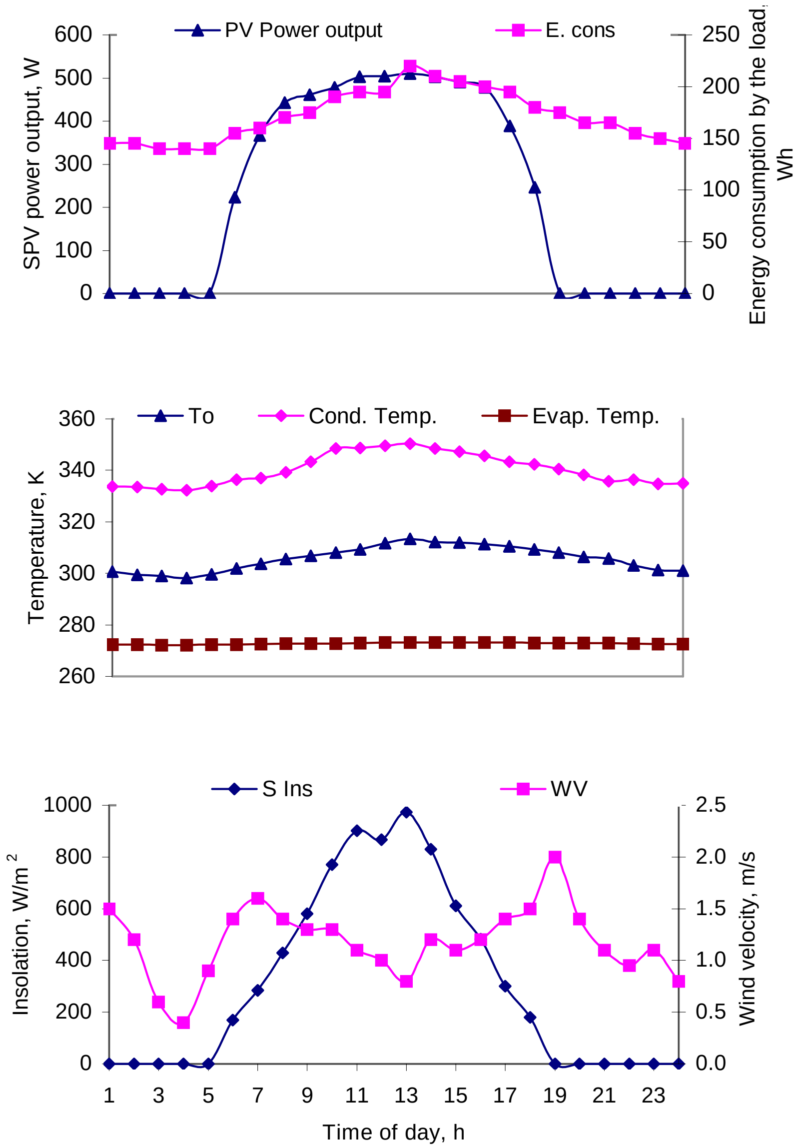

Figure 9. Effect of weather conditions on the SPV power output, 2 X 7 combination, and energy consumption by vapour compression cooling system under full load (with stored potatoes and with circulation of air inside cold store) during tested sunny days in summer 2001.

$$E_{cons} = -7780.36 + 2.6457\ T_3 + 25.8567\ T_4 \qquad R^2 = 0.956 \qquad (27)$$

Where: $(332.3 \leq T_3 \leq 350.3)$, K and $(272.1 \leq T_4 \leq 273.2)$, K

The average daily SPV oversizing ranged between 24.49 to 27.51% during tested days. It appears that, the PV modules were capable of meeting the energy consumption by cooling system. Analysis of the data indicated that insolation is highly significant (1%) affects the SPV energy output and energy consumption, while it is significantly (5%) affects the oversizing.

The percentage of the above component is calculated with respect to the installed cooling capacity as shown in Figure 10. The calculated component revealed that the higher load percentage is related to heat content of the potatoes and respiration, respectively.

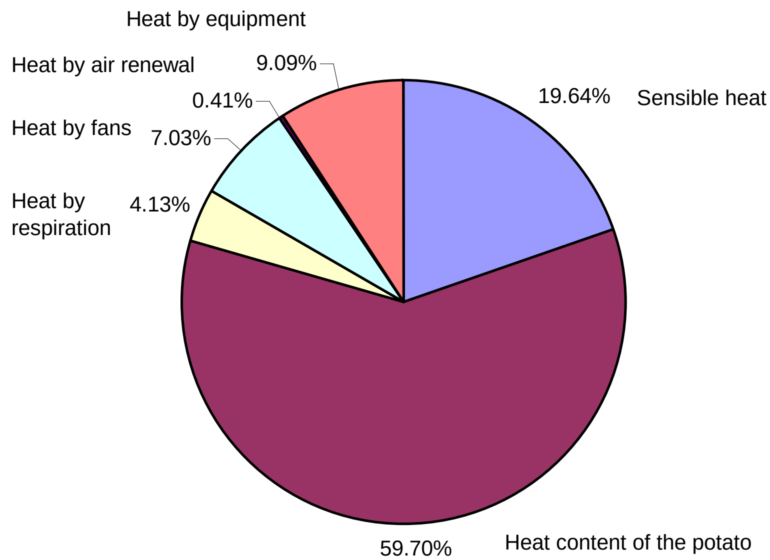

Figure 10. Percentage of the refrigeration load corresponding to components.

3.4 Coefficient of Performance of Refrigeration System

Performance of cooling system powered by SPV for loaded and air circulated cold storage structure as affected by weather conditions which could be calculated based of Figure 9. The actual COP varied from 2.83 to 3.62 during tested sunny days. The average daily overall COP of the cooling system was 3.25 with standard deviation of 0.34 and coefficient of variation of 8.36. The minimum value of COP_{real} of cooling system was calculated at noon hours, while the higher values were calculated at early morning hours. This is attributed to bigger temperature difference between condenser and evaporator at noon hours. The results showed that the COP of cooling system decreases, and power consumption increases as we go to lower refrigeration temperatures.

The recorded data revealed that the COP_{real} for loaded and air circulated cold storage structure is lower than that of empty and air circulated case. This is attributed to heat generated by potatoes during respiration process, in addition to larger temperature difference between condenser and evaporator.

Analysis of data indicated that insolation and ambient temperature significantly (1%) affected the COP_{real}. The correlation between COP_{real} of cooling system, and ambient conditions in case of loaded and air circulated cold storage structure during tested sunny days can be expressed as follows:

$$COP_{real} = 14.9871 - 0.0005\, S_{Ins} - 0.0558\, WV - 0.0350\, T_o \qquad R^2 = 0.971 \qquad (28)$$

Where: $0 \le S_{Ins} \le 973.46$, W/m^2, $0.4 \le WV \le 2.0$, m/s and

$298.3 \leq T_o \leq 313.4$, K

3.5 Overall Efficiency of the Designed Systems

The overall efficiency, η_{Total}, of the entire system, by considering different losses was,

Panel efficiency (η_p) = 10.36%,
Battery efficiency (η_B) = 80%,
Inverter efficiency (η_{PCS}) = 90% and
Cooling system efficiency ($\eta_{cooling}$) = 80%

$$\eta_{Total} = \eta_p \text{ X } \eta_B \text{ X } \eta_{PCS} \text{ X } \eta_{cooling} = 0.1036 \text{ X } 0.80 \text{ X } 0.90 \text{ X } 0.80 = 5.97\% \qquad (29)$$

3.6 Cost Evaluation of 1.0 m^3 EC And 2.5 m^3 Cold Storage Structures

The initial costs and economical analysis of SPV system, rice straw pad structure; storage structure and cooling system have been given through Tables 5, 6, 7 and 8, respectively. The cost economics of storing (curing) potato in the EC structure indicated that the cost of curing one kg of potato in the 1.0 m^3 rice straw pad structure would be Rs. 0.57.

The cost economics of storing potato in the cold storage structure indicated that the cost of storing one kg of potato in the 2.5 m^3 storage structure would be Rs. 0.44. It can be seen from initial costs of the storage structure that the insulation material had affected significantly on the structure cost. Therefore, optimization of insulation thickness should be considered to justify the investment.

The cost economics of cooling system attached to 2.5 m^3 storage structure, which is able to produce 0.180 tonne refrigeration indicated that the cost of cooling one kg of potato would be Rs. 0.90. Obviously, considering the initial cost, the compressor had higher cost with respect to other components. Therefore, the compressor should take least energy, within a wide range of operation.

Considering the cost of unit energy generated by PV system, which is required to operate the cooling system (Rs 4.86/kWh), the total cost would be Rs 9.02. If the cost of energy produced by petrol-kerosene generator and grid electricity is 10.47 and 3.5 Rs/kWh, the total cost would be 14.63 and 7.66 Rs/kg, respectively. In the rural or remote areas where cold storage facilities and grid electricity are not available or far off, the existence of such project can be recommended for long term storage of horticultural produce like potatoes, and therefore, the additional investment is justified with long run.

In the calculation of curing and cold storage cost of potato, it was assumed that the potato was cured for about 60 days and stored for 150 days, in the EC and cold storage structures, and no other use was envisaged for the remaining period in a year. Thus, the entire fixed cost was accounted for that period only. However, if the entire system could be used for other crops during the remaining period of the year, the fixed cost would be distributed over the entire year and the fraction of the fixed cost for potato storage would be considerably reduced.

The additional cost involvement due to application of fungicides/sprout suppressants, which accounts for about Rs 0.14/kg of potato may be considered. Where the cost of this chemical can be recovered by preventing sprouting, reduction of physiological loss in weight and rottage of potato tubers. Considering the initial cost of potato is Rs 2.00/kg then: Total break-even cost of curing and cold storage structures, and cooling system

= 0.57 + 0.44 + 0.902 +2.00 = Rs 3.91/kg

Considering 6% weight loss during storage due to transpiration, respiration, etc.,
Break-even cost = 3.91 /0.94 = Rs 4.16/kg

Table 5. Economic parameters and optimization of power systems to operate vapour compression cooling system for potato storage (0.180 tonne refrigeration).

Item/option a. General parameters		
1. Discount rate General inflation rate Fuel inflation rate	10% 5.0% 8%	
b. Solar PV system	With subsidies	Without subsidies
Installed capacity	490 W (14 module @ 35 W_p each)	
Energy output	4.50 kWh/d	
Capital cost of PV modules including manual tracking system and installation	Rs 30,000/0.49 kW	Rs 77,000/0.49 kW
Capital cost of batteries	Rs 7000/4.32 kWh (2 batteries @ 2.160 kWh each)	
Capital cost of inverter 1.0 kW	Rs 6000/kW	
Useful life of modules	20 years	
Useful life of batteries	3 years	
Useful life of inverter	15 years	
Labour and overhead	1% of capital cost	
Maintenance cost	1% of capital cost	
Calculated annual costs		
Annualized cost of PV modules, Rs = 30000 X 0.11746 =3523.79		9044.42
Annualized cost of batteries, Rs = 7000 X 0.40211 = 2814.804		
Annualized cost of inverter, Rs = 6000 X 0.131474 = 788.8		
Total annualized cost of PV system, Rs = 7127.394		12648.024
Annual labour and overhead cost, Rs = 0.01 X 43000 = 430		900
Annual maintenance cost, Rs = 0.01 X 43000 = 430		900
Total annual costs, Rs = 7987.394		14448.024
Unit cost of PV electricity, Rs/kWh = 7987.394/(4.50 X 365) = 4.863		8.796
c. Petrol-kerosene generator parameters		

Capital cost of petrol-kerosene generator including cost of spares and wires	Rs 16000/0.81 kW
Rated power, kW	0.81
Useful life of generator (electricity available round the clock), years	5
Inspection/maintenance cost (% of capital cost)	10
Average fuel consumption, l/h	0.37 (8.88 l/d)
Fuel cost, Rs/l	20.00
Calculated annual costs	
Annualized capital cost of petrol generator, Rs = 16000 X 0.264 = 4224.0	
Annualized cost of fuel, Rs = (8.88 l/d) X (20.0 Rs/l) X 365 X 5 years X 0.211247 = 68469.378	
Annual maintenance cost, Rs = 16000 X 0.1 = 1600	
Total annual cost, Rs = 4224.0 + 68469.378 + 1600 = 74293.378	
Unit cost of electricity generated by petrol-kerosene generator, Rs/kWh = 74293.378/(0.81 x 24 X 365) = 10.47	

d. Grid electricity

Cost/kWh includes the cost of wiring	Rs 3.50/kWh

Table 6. Cost economics analysis of evaporatively cooled rice straw pad structure.

A. Fixed cost	Cost, Rupees
i. Cost of the structure (excluding rice straw pad and jute sack)	2677.00
ii. Life of unit	10 years
iii. Salvage value (10% initial cost)	267.70
iv. Depreciation per year {(2677 – 267.7)/10}	240.93
v. Cost per year (iv)	240.93
vi. Cost per kg of potato = $\frac{Fixed\ cost\ per\ year}{Quantity\ of\ potatoes\ (550\ kg)}$	0.44

B. Variable cost (Annual)

vii. Cost of replacement of cooling rice straw pads	negligible
viii. Cost of replacement of jute sacks	70.00

ix. Total variable cost (vii + viii)	70.00
x. Cost per kg of potato = $\frac{Total\ annual\ variable\ cost}{Quantity\ of\ potatoes\ (550\ kg)}$	0.13
Total cost of curing potatoes in EC structure (vi + x)	Rs 0.57/kg

Table 7. Cost economics analysis of the 2.5 m^3 cold storage structure.

A. Fixed cost	Cost, Rupees
i. Cost of the structure (excluding colour paint and plastic sheet)	7985.5
ii. Life of unit	50 years
iii. Salvage value (10% initial cost)	798.55
iv. Depreciation per year {(7985.5 – 798.55)/50}	14.3739
v. Cost per year (iv)	14.3739
vi. Cost per kg of potato = $\frac{Fixed\ cost\ per\ year}{Quantity\ of\ potatoes\ (550\ kg)}$	0.26
B. Variable cost (Annual)	
vii. Cost of replacement of colour paint	48
viii. Cost of replacement of plastic sheet	50.4
ix. Total variable cost (vii + viii)	98.4
x. Cost per kg of potato = $\frac{Total\ annual\ variable\ cost}{Quantity\ of\ potatoes\ (550\ kg)}$	0.18
Total cost of potato storage in the storage structure (vi + x)	Rs 0.44/kg

Table 8. Cost economics analysis of cooling system (0.180 tonne refrigeration) attached to 2.5 m^3 storage structure.

A. Fixed cost	Cost, Rupees
i. Cost of the structure (excluded thermostat and spare parts)	5770
ii. Life of unit	15 years
iii. Salvage value (10% initial cost)	577.0
iv. Depreciation per year {(5770– 577.0)/15}	346.2
v. Cost per year (iv)	346.2
vi. Cost per kg of potato = $\frac{Fixed\ cost\ per\ year}{Quantity\ of\ potatoes\ (550\ kg)}$	0.623
B. Variable cost (Annual)	
vii. Cost of replacement of thermostat	70
viii. Cost of replacement of spare parts	80
ix. Total variable cost (vii + viii)	150

x. Cost per kg of potato = $\frac{\text{Total annual variable cost}}{\text{Quantity of potatoes (550 kg)}}$	0.273
Total cost of cooling system used for storage of potato (vi + x)	Rs 0.902

The total cost of curing and storing 1.0 kg of potatoes using the proposed 25.0 m^3 EC rice straw pad structure, 50.0 m^3 cold storage structure and cooling system able to produce 1.0 tonne refrigeration, and operated by 2.21 kW subsidized PV system, considering the weight loss of potatoes 6% would be Rs 7.96. While the total cost for the same system operated by grid electricity (Rs 3.5/kWh) and petrol-kerosene generator (Rs 9.36/kWh) would be 7.02 and 12.88 Rs/kg, respectively.

The price of potato during off season, July-September, usually remain close to or higher than the above total break-even cost of a subsidized PV system and grid electricity operating cold storage. Hence, the PV system becomes highly competitive with the conventional grid electricity generation.

4. CONCLUSION

- The average daily PV module conversion efficiency of 8.90, 7.77 and 10.74% corresponding to module temperature of 317.7, 318.3 and 299.1 K were recorded for clear sunny days during summer 2001, 2002 and winter 2002, respectively.
- The energy supply from the solar panel (490W) charged the battery for overnight operation of the cooling system. It was found that the energy supply from the panels was reduced under full load by 33.6%. It was found that the output power was oversized than the load demanded by the cooling system on full load by an average of 26.53%.
- The average daily SPV power output and energy consumption by cooling system under full load (with stored commodity and air circulated cold store) were 5.60 and 4.115 kWh/d, respectively.
- The actual COP for loaded and air circulated cold storage structure varied from 2.83 to 3.62 with an average daily of 3.25 during tested sunny days.
- The overall efficiency of the entire system, by considering different losses was 5.97%.
- The average inside temperatures of 285.39, 280.94 and 283.13 K and inside relative humidities of 73.94, 81.21and 86% were recorded for empty and non-air circulated, empty and air circulated, and loaded and air circulated storage structure, respectively, during experimentation.
- The total cost of curing and storing 1.0 kg of potatoes inside 2.5 m^3 cold store operated by subsidized PV system, considering the weight loss of potatoes at 6%, would be Rs 9.02. While the total cost for the same system operated by grid electricity (Rs 3.5/kWh) and petrol-kerosene generator (Rs 10.47/kWh) would be 7.66 and 14.63 Rs/kg, respectively.

- The total cost of curing and storing 1.0 kg of potatoes using the proposed 25.0 m^3 EC rice straw pad structure, 50.0 m^3 cold storage structure and cooling system able to produce 1.0 tonne refrigeration, and operated by 2.21 kW subsidized PV system, considering the weight loss of potatoes 6% would be Rs 7.96. While the total cost for the same system operated by grid electricity (Rs. 3.5/kWh) and petrol-kerosene generator (Rs 9.36/kWh) would be 7.02 and 12.88 Rs/kg, respectively.
- Several multiple regression equations were obtained and can be used to predict the PV panel power output and its temperature in addition to energy consumption by the cooling system and its performance.

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