Energy Efficient Design of Cold Storage

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Abstract

Cold storages are used for the preservation of food items so that their availability is maintained throughout the year. Food storage is highly expensive in tropical countries because it consumes a lot of energy for refrigeration. Retrofitting the cold storage with sustainable measures may decrease both the energy demand and its operational cost, as examined through a case study of a potato cold storage located in a tropical city. The major contribution in energy demand comes due to the heat transfer through the built envelope and the heat dissipated by the food items. The contribution from the envelope heat transfer can be decreased by using the green wall as it decreases the temperature difference between the interior and exterior surfaces of the wall. The green wall reduces the sensible heating load of the cold storage approximately by 43% and inside temperature approximately by 10-20%. Incorporating a geothermal loop in the condenser section of the refrigeration plant helps to decrease both the sink temperature and water consumption. This method is very useful in those countries which have water scarcity. It decreases the condenser temperature by approximately 10-15 ^{0}C thus leading to an increase of Coefficient of Performance (COP) of the refrigeration plant. Most of the cold storages are designed for about 2-3 ^{0}C temperature being suitable only for potatoes, whereas other agricultural products e.g. fruits and seasonal vegetables get wasted due to the unavailability of storage facilities. Using a cascaded vapour compression (V-C) refrigeration system can decrease the energy consumption and also provide a range of temperatures for storage of a variety of food items. The lower temperature V-C cycle will help for the storage of potatoes, while the higher temperature V-C cycle will facilitate the storage of other food items such as fruits and vegetables. Hence, the cascading of low temperature V-C cycle (refrigerant R-134a) with higher temperature V-C cycle (refrigerant R-22) along with geothermal loop for condenser cooling can prove to be an effective solution to reduce the energy demand. The implementation of these solutions may help the cold storage units to reduce their net operating cost. A detailed study on model cold storage shows that after applying changes in the system design, the operating cost decreases significantly. The modified cold storage is designed for cooling load of 110 TR for potatoes and 60 TR for fruits and

vegetables. The cold storage currently has an electricity bill of 1.6 million rupees per month, but after applying the changes in system design, it may reduce to 1 million rupees per month approximately. The emission levels also decrease by approximately 30%, thus providing both the environmental and economic benefits..

Keywords: Industrial Sustainability, Thermal System Design, Refrigeration System, Built Envelope, Cold storage.

1. INTRODUCTION

There is an increase in demand for cold storage facilities that are involved in the food sector for the maintenance of food quality and food security. The carbon footprint associated with food loss is 3.3 Gt of CO_{2e} (FAO, 2015). The total capacity of refrigerated warehouses worldwide is 616 million cubic meters, and India has 150 million cubic meters capacity with 7,645 cold stores (GCCA, 2018). Cold storage is an energy-intensive sector, it consumes an average of 25 kWh of electricity and 9,200 Btu of natural gas per square foot per year (CSCS, 2018). Nearly 2.5% of the global greenhouse gas (GHG) emission (direct and indirect) is due to the cold chain (Evans et al. 2013). Soltani et al. (2020) suggested a combined cooling, heating and power system with a gas engine to provide energy demand of commercial cold storage which lowers the fuel consumption and system operating cost about 78.85% and 81.34%, respectively. Another cold energy management strategy is the use of thermal energy storage systems (Zhao et al. 2013). Messineo (2012) proposes the use of R744-R717 cascade refrigeration system and compares the behavior with conventional R404 two-stage refrigeration systems for low evaporative temperature (-30 ℃ $to - 50$℃). Giannetti et al. (2015) suggest a cascading system combining a VCRC and inverse Brayton cycle to produce low temperature and also solves the problem of defroster and fan. Kilicarslan & Hosoz, (2010) give the result that R717-R23 refrigerant coupled cycles have maximum COP and lowest irreversibility in cascade refrigeration systems. By giving optimum working condition for CO_2/NH_3 optimum exergetic efficiency comes out to be 45.89% which leads to total cost rate of 0.01099US$ (Aminyavari et al. 2014).

Geothermal loop or earth tube heat exchanger (ETHE) is another method to improve the system COP and to reduce the cooling water requirement of condensers in areas where water scarcity is the problem. Alghannam (2012) investigated the performance of ETHE in terms of COP and was able to attain an average COP 6.32 and peak of 6.89 on sandy soil on the arid desert climate. The ETHE techniques have good cooling potential which can exceed 15℃ on hot days (Hamdi et al. 2018). Chauhan et al. (2015) have developed ETHE for use in a greenhouse in arid areas like Kutch. Proper insulation and covering of the building envelope also contributes to a great reduction in cooling load of cold storage. Manso & Castro-Gomes, (2015) suggest an application of green vegetation on the building walls and gives a review of different kinds of green walls and their characteristics. The difference in the temperature between the bare wall and covered with vegetation ranges from minimum 12℃ to maximum 20℃ (Mazzali et al. 2013). Susrova et al. (2013) develops a mathematical model of an exterior wall covered with climbing vegetation which results in improvement of overall resistance by 0.0 to 0.7m^2K/W.

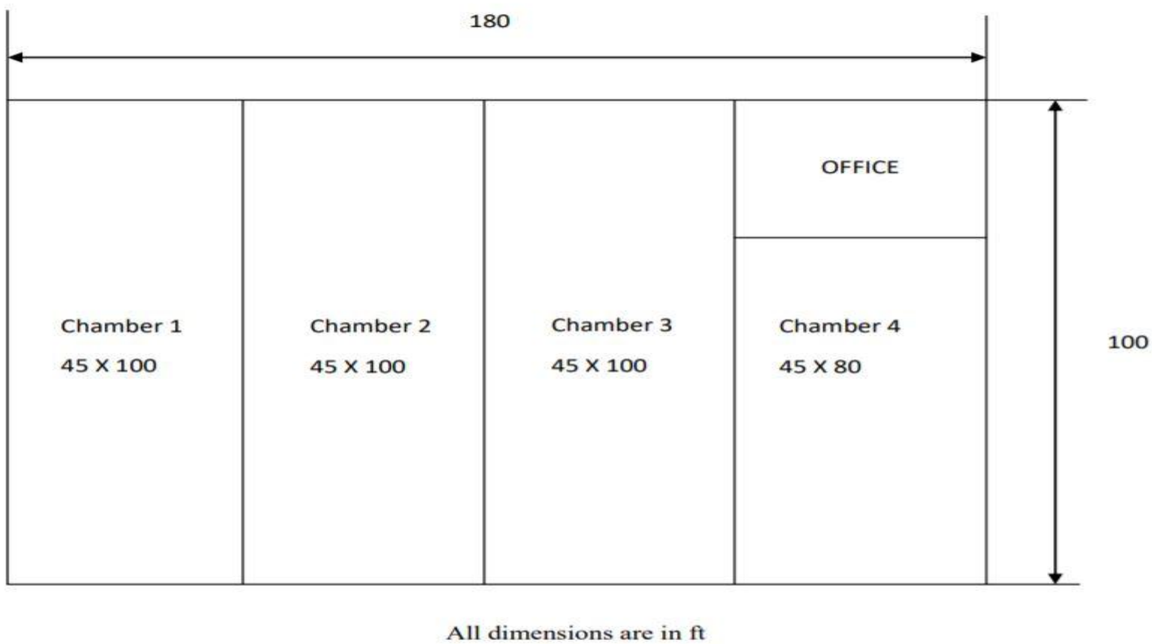
The study proposes retrofitting in a cold storage present in Prayagraj (Uttar Pradesh) to improve the performance of the cooling system and reduce the operational cost of the cold storage. The study suggested the application of green wall to the built envelope for reducing envelope thermal load. Further, it examines the use of geothermal loop and cascade refrigeration system for multi-product cold storage. The proposed sustainable systems can improve the cold storage infrastructure of the country with enhanced economic benefits.

2. METHODOLOGY

The project site which is under the study criteria named Farrukhabad Cold Storage (Latitude- 24.4920°N; Longitude- 81.8600°E) is situated in Prayagraj (U.P.) India. In this study, the plant survey was carried out and the building details along with refrigeration system details were collected from the site location. It has a storage capacity of 5000 metric tons and is used to store only potatoes. It has four chambers to store potatoes, three chambers are of the same dimensions and one chamber is of different dimensions. There are wooden stacks in which potatoes are stored in sacks of 50 kg each. Figure 1(a) shows the photographic image of the cold storage, Figure 1(b) shows the satellite image of the cold storage and Figure 1(c) shows the plan view of the cold storage.

(a)

(b)



(c)

Figure 1. (a) Photographic image of Cold Storage, (b) Satellite image of Cold Storage, (c) Plan View of the Cold Storage.

2.1 LOAD CALCULATIONS

Table 1 shows the general specifications of the selected cold storage. The inside of the wall has a layer of glass wool supported by a plywood board which acts as an insulation for the cold storage.

Table 1. General Specifications of the Cold Storage

Product	Potatoes
Location	Prayagraj, Uttar Pradesh
Outside Temperature	+45°C maximum DB, +30°C WB (1130 F/860 F)
Product Loading Temperature	20 °C - 25 °C maximum
Weight of each bag	50 kg
Total Storage Capacity	5000 metric ton
Chamber Size	100ft Lx45ft Wx 45ft H (3 Chambers) 80ft Lx45ft Wx 45ft H(1 chamber) (Total Volume = 769500 ft3 , Total Floor Area = 17100 sq ft)
Loading Rate	50 ton for 1 chamber (maximum)
Pull Down Time	15 °C in 24 hrs
Compressor Running Hours	20 hrs/day during pull down
Ventilation Requirements	2 to 6 air changes per day
Heat of Respiration	1350-1870 J/kg per 24 hours
Specific Heat of Potato above freezing	3.433 kJ/kg.K
Refrigeration System	Vapour Compression System
Refrigerant	R 22
Suction Pressure	1.5 bar
Discharge Pressure	19 bar
Storage Temperature	2°C
Number of Compressor	15
Compressor Capacity	23 horsepower (hp) (i.e. 1 hp = 745.5 Watts)
Total Refrigeration capacity (for potatoes only)	110 ton of refrigeration (TR) (i.e. 1TR = 3.5 kW)

2.2 Thermal Loads

Transmission Load: This load is due to the transmission of solar radiation and heat transfer through the walls and roof based on the design specifications and materials used.

Product Load: Product Load is the load on the refrigeration system due to the loading temperature and the storage temperature.

Product Load = Loading Rate * Specific Heat * Temperature Difference.

Respiration Load: Assuming that the remaining (5000-50 = 4950 ton) potatoes are already in store, and refrigeration load on the last day of loading is considered.

It is calculated using the equation.

Respiration Load = Mass of Potatoes * Heat of Respiration.

Lighting Load: Lighting Load is the load on the Refrigeration System due to the lights used in the cold storage.

Infiltration Load: Based on 4 air changes/day, outside enthalpy at 45 °C DB and 30 °C WB, inside enthalpy at 2 °C and 90% RH have been taken from psychrometric property tables for moist air and 70% recovery is also considered.

Miscellaneous Load: Load on the refrigeration system due to the fan motors, human occupancy etc. It is evaluated using the specifications of the fan motors, number of people during loading time, etc.

2.2 GREEN WALL

For a possible reduction of the thermal load of the cold storage, use of green wall is proposed to improve the thermal properties of the built envelope. To estimate the thermal load reduction with a green wall, an experimental model was investigated.

The objective of the experiment was to determine how much the temperature difference between interior and exterior surface of the wall is reduced by adding a green wall. In the experiment, a cubicle built envelope of dimensions (1.5x1.3x1.03 m^3) was constructed with similar design specification of cold storage wall. Image of the experimental model is depicted in Figures 2 (a, b, c & d). The thickness of the wall of the cubicle was 11 inches which comprises two layers of cement mortar and one layer of fireclay brick. The readings of the inside and outside surface of the wall temperature were taken by using a temperature gun and the ambient temperature was taken by thermometer.

The model is operated in two different conditions.

(1) Mode 1 (without Green Wall)

(2) Mode 2 (with Green Wall)

MODE 1

In this model, the wall of the cubicle has been exposed to the ambient and the direct solar radiations are falling on the wall without any intervention between the wall and surroundings. The temperature readings are expected to be higher as there is no intervention. Temperature readings were recorded at regular intervals of 1 hour.

MODE 2

In this model, the cubicle has been exposed to the ambient through the green wall in between the outside surface of the wall and the surroundings. Temperature readings of inside and outside surface of the wall were simultaneously measured by a temperature gun.

(a) (b)

(c) (d)

Figure 2. (a) Cubicle without Green Wall, (b) Temperature Measurement, (c) Cubicle with Green Wall, (d) Temperature Measurement

2.4 GEOTHERMAL LOOP

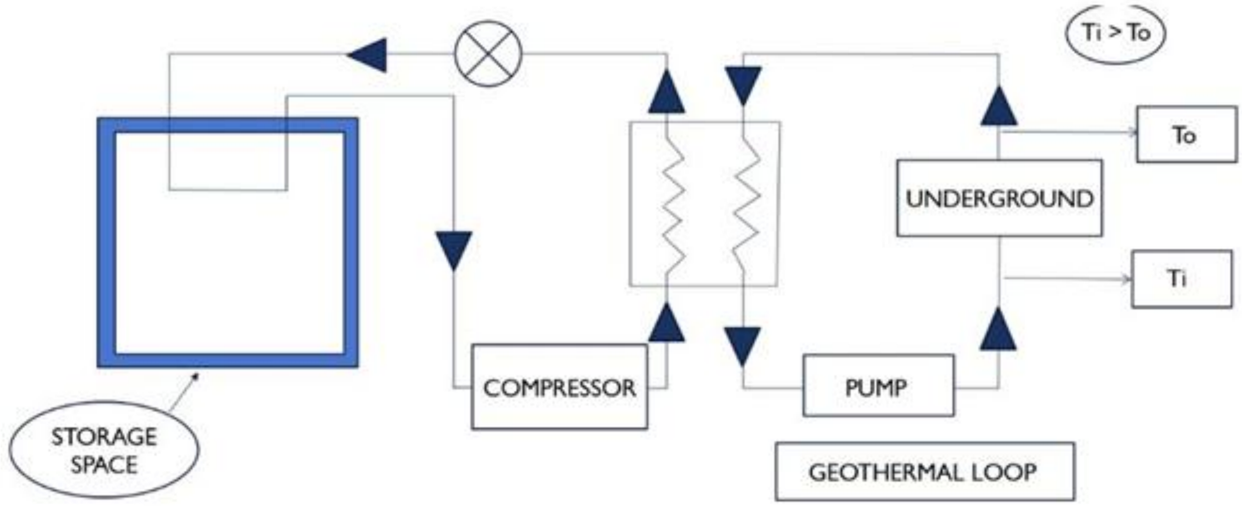


Figure 3. Schematic Diagram of Geothermal Loop

Schematic diagram of geothermal loop is depicted in Figure 3. The simulation of the geothermal loop was done in ANSYS FLUENT software used for computational fluid dynamics (CFD) analysis. First the geometry of the pipe was made and meshing was done, after that the boundary conditions were given to the geometry.

In thermal simulation, the depth of around 4 m is considered because at this depth the ground temperature remains constant throughout the year (i.e. 20 °C). The diameter of pipe is considered as 5 cm and the inlet fluid temperature is considered as 33 °C. The velocity range is taken between 1 - 3 m/s; with pipe length between 10-30 m. The outlet temperature was calculated for different scenarios and the number of tubes required for the desired flow in the condenser was also calculated. The outlet of around 25°C was expected and by keeping that temperature and with some temperature differential between the condenser and geothermal loop, the condenser can be kept at around 30°C.

It has been calculated using the Dittus Boelter Equation for turbulent flow through the pipe.

Nusselt Number = 0.023*(Reynolds Number)^0.8 * (Prandtl Number)^n

Where n = 0.3 for cooling

n = 0.4 for heating

2.5 CASCADED REFRIGERATION SYSTEM

Schematic diagram of proposed system is depicted in Figure 4. Evaporator 1 is for the cooling load of the potato chamber, Evaporator 2 is for the cooling load of the fruits and vegetables chamber and Evaporator 3 is the sink of the potato chamber. Condenser 1 is for the potato chamber and Condenser 2 is for the fruits and vegetables chamber. Table 2 represents the details of the cascaded system.

Table2. Refrigeration System Details of the Cascaded Cold Storage

Refrigerant (Lower VC Cycle)	R 22
Refrigerant (Upper VC Cycle)	R 134a
Evaporator Pressure (Lower Cycle)	3 bar
Condenser Pressure (Lower Cycle)	6 bar
Evaporator Pressure (Upper Cycle)	2.5bar
Condenser Pressure (Upper Cycle)	7.5 bar
Coefficient of Performance (COP) (Lower Cycle)	9
COP (Upper Cycle)	5

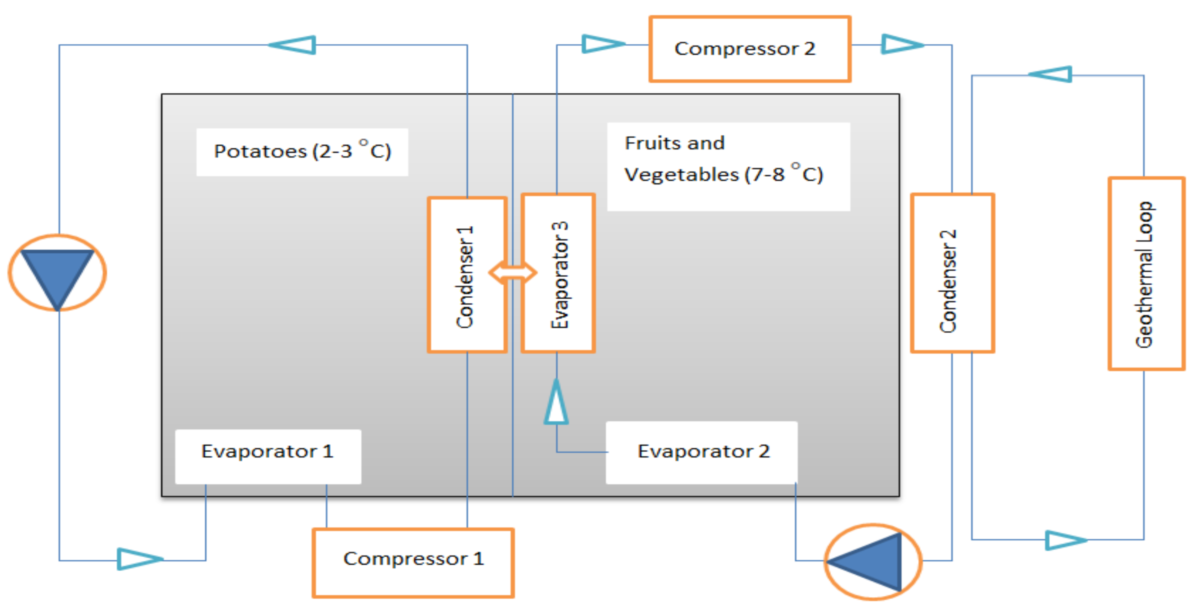
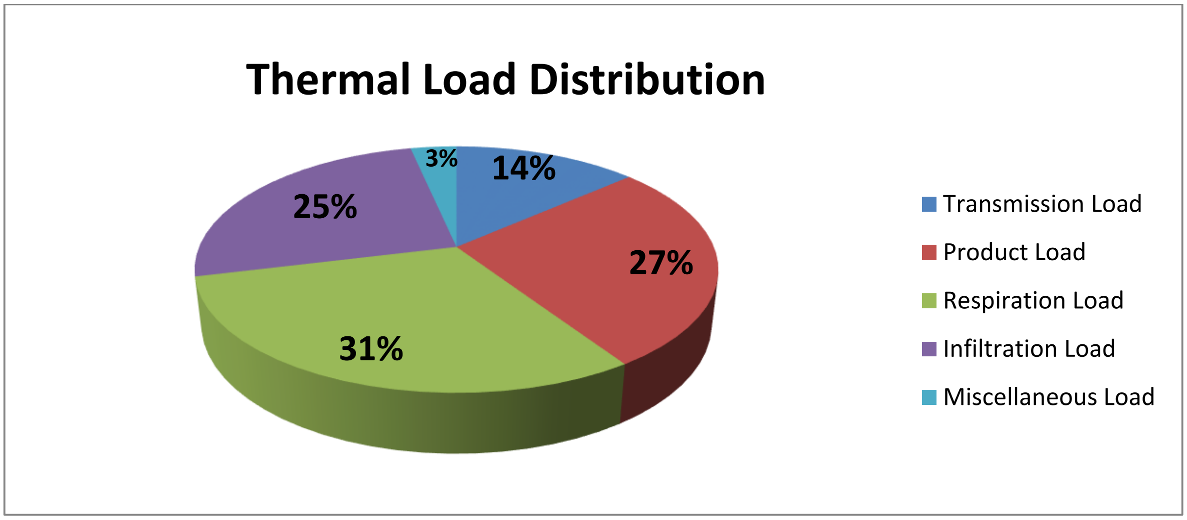


Figure 4. Schematic diagram of proposed system

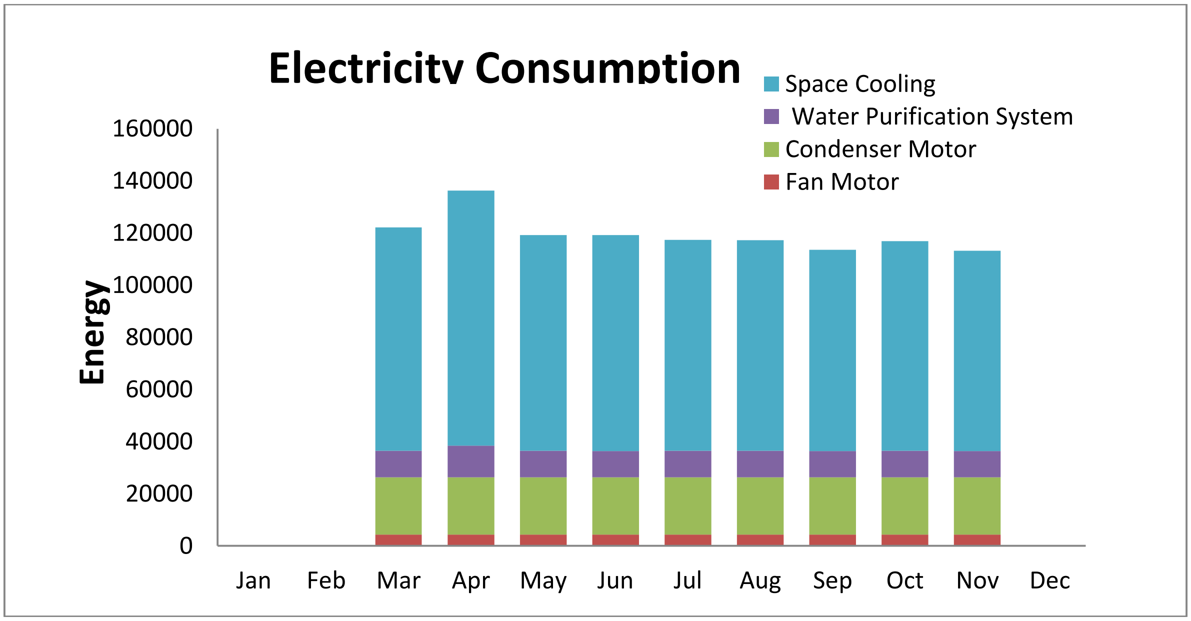
3 RESULTS AND DISCUSSION

3.1 Load Calculations

Figure 5(a) shows how the space cooling is distributed between various types of loads that exist in the storage space. Figure 5(b) shows the energy consumption of the various equipment used in the cold storage. Figure 5(c) shows the monthly energy consumption of the loads in space cooling. Energy Consumption in the month of April is highest because at this time the loading of the potatoes takes place and between December to March the cold storage is not used so the energy used in space cooling is nil.



(a)



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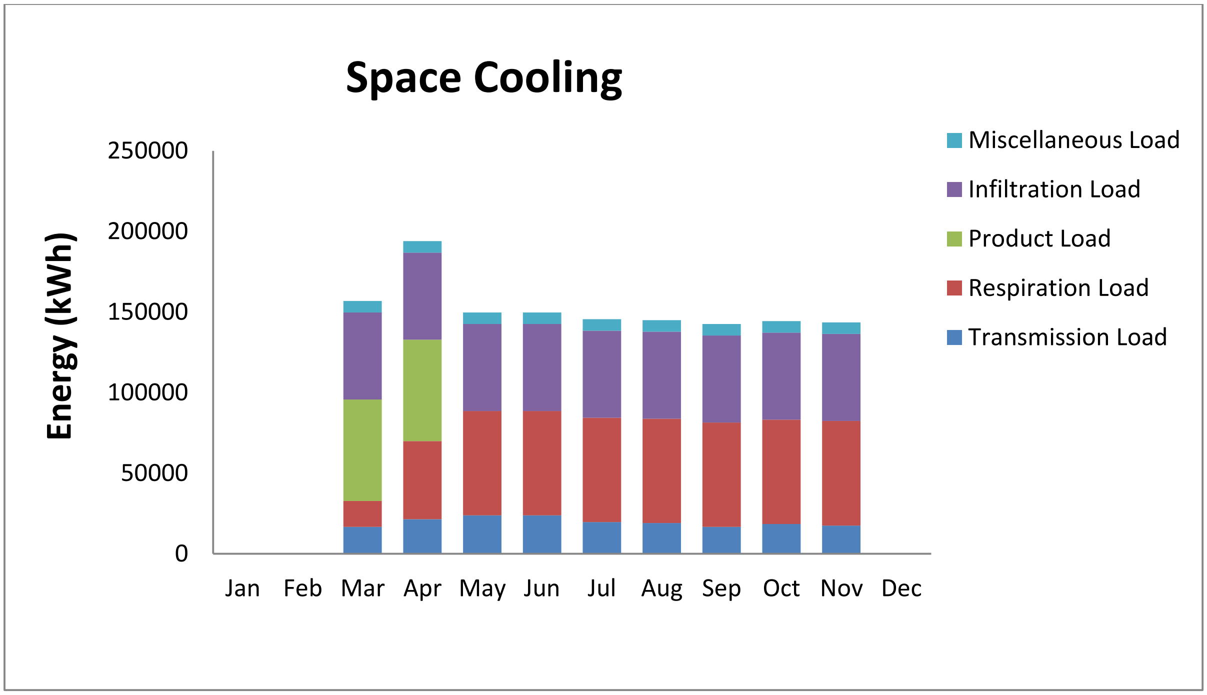


(c)

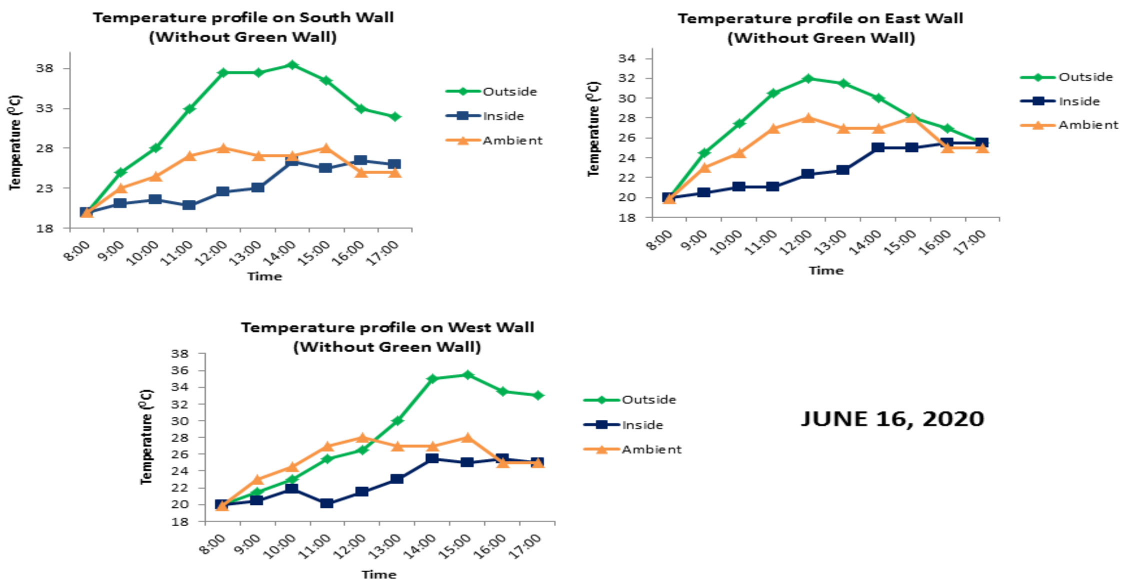
Figure 5. (a) Space Cooling Load Distribution, (b) Electricity Consumption of Equipment (c) Energy Distribution of Space Cooling (Monthly)

Total Cooling Load = Transmission Load + Product load + Respiration load + Infiltration Load + Miscellaneous Load

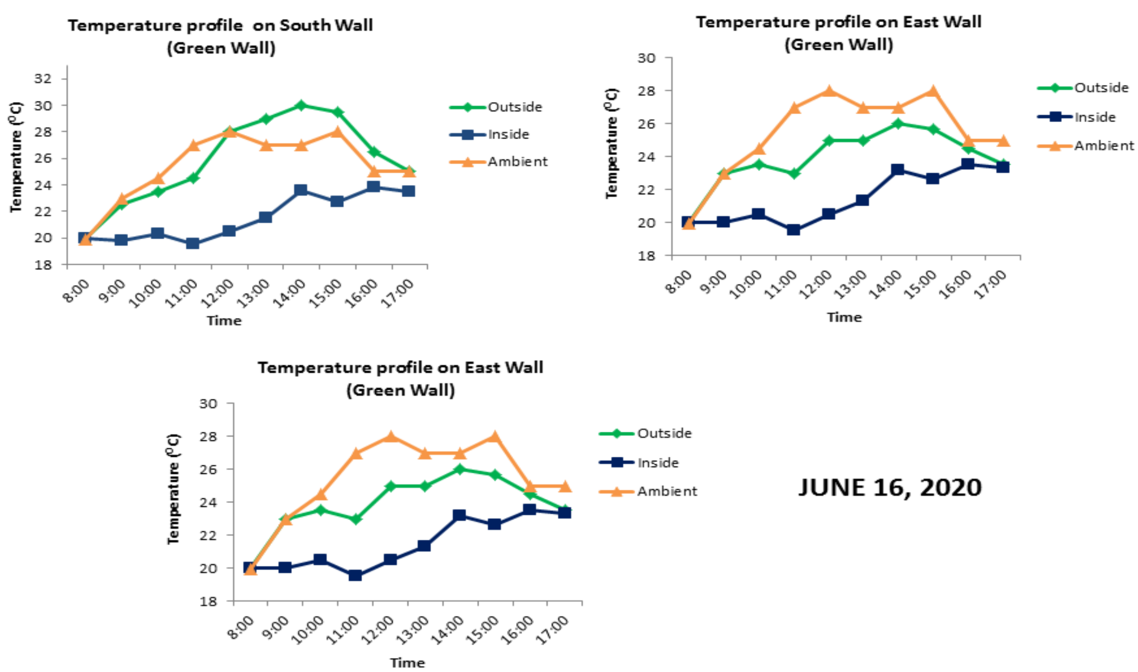
The total cooling load for the cold storage is approximately 110 TR. The electricity consumption in the VC System is 157950 kWh, and carbon emissions are 268 tons per month whereas the electricity consumption in the cascaded VC-VC System is 109980 kWh, and carbon emissions are 187 tons per month.

3.2 Green Wall

The results obtained from the experiment on the green wall application on the cubicle are shown in Figure 6(a) and 6(b). The data of the temperature readings without green wall are shown in Figure 6(a) whereas temperature readings with green wall are shown in Figure 6(b) for the sun facing walls.



(a)



(b)

Figure 6. (a) Temperature Profile of the Cubicle without Green Wall, (b) Temperature Profile of the cubicle with Green Wall

Table3. Sensible Heat Loss through walls

	With Green Wall	Without Green Wall
South	21.87 W/m^2	43.75 W/m^2
East	13.07 W/m^2	28.30 W/m^2
West	22.45 W/m^2	30.56 W/m^2

The percentage reduction in sensible heat load flux as calculated from Table 3 on the south wall, east wall, and west wall are 50%, 53.75% and 26.67% respectively and the average reduction in the flux is 43.47%. Initially the cooling load due to sensible heating was 40 kW and it gets reduced by 17.38 kW due to the green wall. The tonnage of refrigeration reduction is approximately 5 TR. The cold storage system under consideration is potatoes which require high humidity. So the increase in humidity of surrounding air due to the green wall is also beneficial to the cold storage, thereby reducing the water spray requirements.

3.3 Geothermal Loop

The geothermal loop outlet temperature is around 23°C which is sufficient to keep the condenser temperature at 30°C. With this decreased condenser temperature, the work input required for the refrigeration effect will decrease. Thus the COP of the system will increase (Lourdes & Tapia, 2017). The new COP of the system equipped with the geothermal loop is calculated as 5 with the help of P-h diagram. The COP has now increased thus making our system more efficient. Also the added benefit which we are getting from this system is the reduction in the amount of wastage of water in the cooling tower.

Table 4. Results of the Geothermal Loop using Analytical Method

Velocity (m/s)	Volume Flow Rate (m^3/s)	Mass Flow Rate (kg/s)	Heat Transfer Coefficient (W/m^2/K)	Length of Tube (m)	Number of Tubes
1.0	0.00196	1.96	2985.63	26	10
1.5	0.00295	2.95	4129.61	19	7
2.0	0.00393	3.93	5198.28	15	5
2.5	0.00491	4.91	6214.24	13	4
3.0	0.00589	5.89	7190..07	11	3

3.4 Cascaded Refrigeration System

After cascading the VC-VC system, the thermal analysis shows that the COP of VC cycle in the system has increased and the monthly electricity bill also reduces from 1.6 million rupees to 1 million rupees. The emissions also reduce after applying changes in the system design. There is a decrease in the carbon emissions by approximately 35% in VC-VC cascaded system, as compared to the conventional VC system used in the existing cold storage.

3.5 Economic Analysis

Monthly Operational Cost of VC system (Existing System)

No of hours of operation/ day = 20 hours

No of days of operation = 30-31 days

COP = 2 (as recorded)

Cooling load = 110 TR + 60 TR

Unit Electricity cost = 9 rupees/kWh

Operational Cost = {[(cooling load)*(time of operation)*(unit electricity cost)]/ COP} = 1.6 million rupees

Monthly Operational Cost of VC-VC system (cascaded system)

No of hours of operation/ day: 20 hours

No of days of operation: 30-31 days

COP (lower temperature cycle): 9

COP (higher temperature cycle): 5

Operational Cost of lower temperature cycle = {[(cooling load)*(time of operation)*(unit electricity cost)]/ COP} = 0.475 million rupees

Operational Cost of higher temperature cycle = {[(cooling load)*(time of operation)*(unit electricity cost)]/ COP} = 0.525 million rupees

Total Operational Cost = 1 million rupees

4. Conclusions

The energy-efficient design of the potato cold storage reduces the electricity demand with associated carbon emissions. Modification in the system design using a cascade refrigeration system reduces the energy consumption by about 35% as well as provides additional facility of medium temperature refrigeration for fruits and vegetables. There is a further potential of reducing energy consumption by incorporating green walls in the cold storage. As an additional benefit, the proposed geothermal loop for condenser cooling will save the evaporative water loss in the cooling towers.

The reduced cost in the operations leads to decrease in the cost of storage and it will help the farmers as they can store their produce at low cost which will help them economically and will also reduce the wastage of their produce.

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