PORTABLE SOLAR REFRIGERATOR WITH BATTERY BACKUP

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Bachelors of Mechanical Engineering

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ABSTRACT

This report presents comprehensive details of the progress of our Final Year Design Project i.e., a Portable Solar Refrigerator with a Battery Backup. The project addresses the problem of inadequate cold storage available for farmers in remote areas and aims to solve it by building a solar-powered, energy-efficient refrigeration unit with a backup battery.

The paper begins with a brief introduction to the problem statement, and defines the objectives of the project, followed by an in-depth exploration of the literature review. The subsequent chapters elucidate the details of the methodology adopted for the design, and analysis of the obtained results. Key aspects of the design include Cooling Load Calculation. Compressor and Solar-Plate Selection, Heat Exchanger Design, and Selection of Throttling Devices and Thermostat.

Through this thorough examination, the report sheds light on the progress so far, offering valuable insights into the development of the Portable Solar Refrigerator with a Battery Backup.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABBREVIATIONS

HE	Heat exchanger
COP	Coefficient of performance
RH	Relative humidity
LMTD	Log mean temperature difference
DC	Direct current

NOMENCLATURE

$\dot{Q}_{trans}$	Heat gain via transmission, W
$\dot{Q}_{produce}$	Product load, W
$\dot{Q}_{resp}$	Heat generated by respiration, W
$\dot{Q}_{equip}$	Heat generated by equipment, W
$\dot{Q}_{light}$	Wattage of each light, W
$\dot{Q}_{infil}$	Heat added by infiltration air, W
$\dot{Q}_{absorbed}$	Heat absorbed by refrigerant in evaporator, W
$\dot{Q}_{rejected}$	Heat rejected by refrigerant in condenser, W
U	Overall heat transfer coefficient, $W/m^2.°C$
A_{ext}	External heat transfer area of compartment, m^2
A_{evap}	Heat transfer area of evaporator, m^2
A_{cond}	Heat transfer area of condenser, m^2
V_{in}	Internal volume of the refrigerated space, m^3
T_{out}	Ambient temperature of the surrounding, °C
T_{enter}	Temperature of the produce at the time of entering, °C
T_{in}	Internal temperature of the compartment, °C
ΔT_{lm}	Log mean temperature difference, °C
x	Wall thickness, m
k	Thermal conductivity of wall material, W/m.°C
h_i	Inner surface conductance, $W/m^2.°C$
h_o	Outer surface conductance, $W/m^2.°C$
m	Mass of the produce being cooled, kg
c_p	Specific heat capacity, kJ/kg.°C
c_{vol}	Volumetric heat capacity of air, $J/m^3.°C$
t	Run time of the refrigerator, hours
t_{light}	Time for which lights are operational, hours
x_i	Mass fraction of the food constituents
ρ_i	Density of the food constituents
r_c	Number of volume changes per day
r	Compression ratio
F	Correction factor to complex geometry heat exchangers

CHAPTER 1: INTRODUCTION

In recent times, there has been a growing acknowledgement within the global community of the urgent necessity to tackle the problem of post-harvest losses in agriculture, particularly in less developed regions. These losses not only lead to considerable financial hardships for farmers but also worsen food insecurity and add to environmental deterioration. In light of this challenge, our project is focused on the development of a Portable Solar Refrigerator with Battery Backup. This innovative solution is aimed at mitigating post-harvest losses and improving the well-being of farmers by providing a sustainable and off-grid means of preserving agricultural produce.

Motivation of Work

The motivation behind this project stems from the alarming statistics regarding post-harvest losses. Studies have shown that approximately 30% to 40% of fruits and vegetables are lost due to inadequate storage and transportation methods, especially in regions with limited access to electricity and refrigeration facilities. These losses not only represent a substantial waste of resources but also undermine efforts to improve food security and alleviate poverty in rural communities.

Moreover, the impact of post-harvest losses extends beyond economic ramifications. It contributes to food insecurity, hinders economic development, and exacerbates environmental degradation through increased greenhouse gas emissions from decomposing organic matter. Therefore, there is an urgent need for innovative and sustainable solutions to address this multifaceted problem.

Problem Statement

The primary challenge addressed by our project is the lack of accessible and reliable cold storage facilities for farmers, particularly in off-grid and remote areas. Conventional storage methods, such as open trollies, jute sacks, and crates, are susceptible to temperature fluctuations and inadequate ventilation, leading to accelerated spoilage of perishable produce. Additionally, the reliance on fossil fuel-powered refrigeration systems contributes to carbon emissions and further exacerbates environmental degradation.

Objectives of the Project

Our project's aim is to create an all-encompassing solution a compact, portable, and solar-driven cold storage system equipped with battery backup to effectively combat post-harvest losses incurred during both storage and transportation phases. Our specific objectives encompass several key facets:

1. Designing a highly efficient refrigeration mechanism, compact yet powerful enough to uphold ideal storage conditions for perishable produce, all powered by solar energy.
2. Integration of a robust battery backup system to ensure uninterrupted functionality, especially during periods of limited solar exposure or during the night.
3. Implementing cutting-edge insulation materials and strategic design methodologies to minimize thermal losses and optimize energy utilization, thereby maximizing overall efficiency.
4. Development of an intelligent electronic control system, tasked with managing power sources—whether solar or battery—and meticulously monitoring internal conditions such as temperature and humidity within the storage unit.

Ultimately, fabrication of a fully functional prototype—our Portable Solar Refrigerator with Battery Backup—followed by rigorous real-world testing to gauge its performance under varied conditions.

Through the attainment of these objectives, our ultimate goal is to provide farmers with an economically viable, sustainable, and readily accessible solution to curtail post-harvest losses. By doing so, we aspire to not only enhance food security but also foster sustainable agricultural practices within communities.

In the subsequent chapters of this report, we will delve into the detailed design, implementation, and evaluation of our Portable Solar Refrigerator with Battery Backup, culminating in the presentation of our findings and recommendations for future research and development.

CHAPTER 2: LITERATURE REVIEW

Literature Review is crucial as it forms the foundation of any project by providing a comprehensive overview of existing knowledge relevant to a particular topic. This section discusses the main data regarding the portable solar refrigerator gathered through research papers, articles, and blogs.

Introduction To Post-Harvest Losses

Post-harvest losses refer to the deterioration and spoilage of the agricultural produce that takes place between the time the produce is harvested till the time it is consumed. The said degradation impacts both the quality and quantity of the produce. Quality losses include those that affect the nutrient composition, caloric values, and the edibility of the harvested produce. On the other hand, the loss in quantity refers to the loss in the amount of a product.

Severe losses and deterioration of the produce occur after harvest, and it happens mainly due to mechanical damage, poor handling, microorganisms, insects and mites, unawareness, and lack of modern technologies. After harvest, inappropriate handling of agricultural products causes their degradation which in turn causes an increase in their price.

As Pakistan is an agricultural country, post-harvest losses have far-reaching consequences because agriculture is the only source of livelihood for a vast majority of the Pakistani population. According to recent statistics, the total production of fruits and vegetables in Pakistan is nearly 13.764 million tons, out of which it is estimated that nearly 35% to 40% is wasted after harvesting (Ahmada, 2021). These losses represent a considerable waste of resources, including labor, water, energy, and land, further emphasizing the necessity of implementing effective preservation solutions to minimize waste and enhance food security for Pakistan’s population.

To mitigate the above-mentioned challenges and to extend the shelf life of agricultural produce it is necessary to employ proper farming techniques and ensure optimal post-harvest humidity and temperature conditions are maintained, especially during the storage and transportation of the produce. (Kiaya, 2014)

Existing Solutions for Post-Harvest Preservation

As Pakistan is a developing country, the traditional methods of post-harvest preservation are still in practice in an attempt to increase the shelf-life of the produce. One such method is sun-drying i.e., the removal of moisture from the produce through exposure to sunlight. This method is commonly used for fruits, vegetables, and grains in rural areas as the access to refrigeration is limited.

Another better method of preservation is canning, which involves heating the food to kill harmful microorganisms and then sealing it in airtight containers. This method is used for fruits, vegetables, and meat products. Chemical treatments like fungicides and pesticides are also used to minimize the spoilage of produce during storage and transportation.

Fruits and vegetables start deteriorating right after their harvest. To preserve the produce quality different post-harvest techniques are recommended, including hyper cooling, refrigeration, and freezing, modified packaging storage, control atmosphere storage, skin coating, hypobaric or low-pressure storage, irradiation, dehydration, canning high-pressure processing and pulsed light/electric applications. (Post-harvest technology in Pakistan, Agriculture, 2001)

Introduction to Solar Refrigeration Systems

Solar refrigerators harness the power of sunlight in their operation in order to provide cooling capabilities. They offer a sustainable and environmentally friendly solution to address post-harvest losses.

Solar refrigerators typically harness the sun's energy through photovoltaic cells that convert sunlight to electricity, which is then used to power the refrigeration unit. By utilizing solar power, the refrigeration system becomes independent of the grid electricity, making the system advantageous for regions with limited access to conventional power sources.

Studies show that it is technically feasible to convert an existing 1651 refrigerator to a photovoltaic refrigerator. Under normal conditions, the modified system performs similarly to a conventional domestic refrigerator working on grid electricity. (Modi, 2009)

Solar refrigerators are cost-effective over conventional refrigeration systems in the long run. These cost savings are particularly beneficial for rural communities having limited financial resources. Several case studies demonstrate the practicality and impact of implementing solar refrigeration systems in agricultural settings worldwide. For example, in remote areas of sub-Saharan Africa, solar-powered cold storage systems enable farmers to preserve their harvested produce in a much better way. (Rutta, 2022)

Recent Advancements in Vapor Compression Cycle

Most refrigeration units operate on the Vapor Compression Cycle, which is a thermodynamic cycle that operates in a closed loop by making the refrigerant undergo four main processes, i.e., compression, condensation, expansion, and evaporation.

The vapor compression cycle is highly efficient in transferring heat from one location i.e., the interior of the refrigerator to another, i.e., the external environment. In addition to being highly efficient, the cycle is also versatile in applications, highly reliable, compatible with most refrigerants, and easy to control.

While the Vapor Compression Cycle is widely used, it does have some limitations. It can be energy intensive which increases the operating costs, particularly in continuous high-load cooling applications. The cycle also has reduced efficiency at extreme temperatures, i.e., at both high and low. In addition, the complex equipment used in the said cycle can make the system bulky and heavy, particularly in commercial and industrial applications and it also requires regular maintenance which can be a hassle. Lastly, the moving parts in the system, such as the compressors can generate noise and vibration during operation, which can be undesirable in residential, commercial, or sensitive environments.

Recent advancements in the Vapor Compression Cycle are aimed at enhancing energy efficiency. These advancements can be categorized into subcooling cycles, expansion loss recovery cycles, and multi-stage cycles. All these modifications work to improve the vapor compression cycle and have their own benefits and key applications. (Badr, 1990)

Introduction to DC-Powered Solar Refrigerators

Direct Current or DC systems have a unidirectional flow of electric current, unlike Alternating Current or AC systems that reverse the direction of current periodically. DC Systems have gained relevance in solar-powered applications as they are more energy efficient, compatible, and cost-effective as compared to traditional AC systems.

DC systems are known to have lower power surges and lesser power consumption as compared to refrigeration systems operating on conventional AC power, which makes the DC Systems more energy efficient. They are more compatible with newer solar technologies as they can be easily integrated, making the system less expensive and more compact.

For a Cold Storage operating on a Vapor Compression Cycle, the only component that requires external power to operate is the compressor. Compressors operate by increasing the fluid pressure by utilizing external electric energy. Research shows that DC Compressors have low power surges as compared to AC Compressors which improves battery life. Moreover, a high-capacity inverter is required for AC refrigerators which increases the cost and causes problems in system integration.

A study was conducted to run a techno-economic assessment of a converted DC and a conventional AC refrigerator, both of which were powered by photovoltaic cells. Results of the experiment revealed that even though both systems maintained almost the same evaporator temperatures and ran on the same compressor speed, the AC system had relatively higher power consumption and power surges as compared to the DC system. The economic assessment conducted in the same experiment shows that the DC refrigerator reduces the system installation cost by 18% as it eliminates the need for an inverter. (Opoku, 2016)

Another experiment was conducted to evaluate the performance of a Variable Speed Compressor i.e., a VSC-based refrigerator, and its effectiveness with the proposed DC level of voltage toward Solar PV applications. Based on the results, it was concluded that using DC VSC-based PV systems increases the system performance and efficiency and decreases power surges and power consumption as compared to the AC-based PV systems. Moreover, it is recommended to use a VSC-based refrigerator for systems that have a battery pack within the solar PV scheme as the system would be more efficient and economical. (Sabry, 2020)

Further Improvements in Solar Refrigerators

Improvements in solar refrigerators can focus on several areas to enhance their efficiency, reliability, and applicability.

Energy Efficiency can be enhanced by improving the design of the PV panels to maximize sunlight absorption, enhancing thermal insulation to minimize transmission losses, and optimizing the refrigeration cycle to reduce the compressor work,

Exploring advanced refrigeration technologies, such as thermoelectric cooling, magnetic refrigeration, and absorption refrigeration, can lead to more efficient and environmentally friendly solar refrigerators. These technologies offer potential advantages in terms of energy efficiency, reliability, and sustainability compared to traditional vapor compression systems.

Implementing smart technologies that can optimize and control the operation of the solar refrigerator by dynamically adjusting the compressor speed according to external conditions, energy availability, and cooling demands can significantly improve the performance of solar refrigerators.

Continuously exploring cost-effective manufacturing techniques, sourcing affordable materials, and leveraging economies of scale can help reduce the upfront and operational costs of solar refrigerators. Improving the affordability of solar refrigeration technology is crucial for expanding access to sustainable cooling solutions in developing regions and underserved communities where traditional grid infrastructure may be lacking or unreliable.

Insulating Materials for Refrigerators

Transmission losses account for more than 50% of the total cooling load for typical domestic refrigerators, and this value increases considerably when we talk about cold storage as they are more significantly exposed to harsh environmental conditions. The only way to reduce such a significant load is by making use of an efficient insulating material. Thus, insulation plays a critical role in minimizing heat transfer through the walls of the refrigerated space, thereby maintaining cooler temperatures in the compartment, and reducing the compressor work.

There are a lot of experimental and numerical studies conducted to minimize the energy expenditure of household refrigerators which in turn improves their energy efficiency. However, very few of these studies pay attention to the heat transfer from the surroundings to the interior of the refrigerator. A study was conducted on transmission losses in household refrigerators which revealed that maximum i.e., 44% of the heat transfer occurred through the walls of the refrigerator. (Melo, 2000)

Insulating materials play a crucial role by minimizing heat transfer and maintaining the desired temperature inside the refrigerated space. With advancements in refrigeration technologies, there has been a great emphasis on the development of insulating materials that are not only thermally efficient but also environmentally friendly. An ideal insulating material has low thermal conductivity and a high thermal resistance (R-value). Sustainable and non-toxic insulating materials are preferred greatly in today's eco-friendly world. In addition to all this, the insulation should be durable, water-resistant, easy to manufacture, and cost-effective.

Choosing a material with all these properties can be difficult. A study was performed for a refrigeration system in which four different insulation materials namely, Polyurethane Foam, Fumed Silica VIP, Glass Fiber VIP, and Alternate Core VIP, were compared for their thermal, physical, and economic performances. The results were analyzed to compare the said materials on the basis of their transmission gain, carbon footprint, and payback period. Results indicated that the use of VIP reduced the fridge's energy consumption by 19.6% while increasing the inner volume by 148 liters and weight by 2.48 kg as compared to the refrigerator insulated by Polyurethane Foam. (Verma, 2019)

The Best Refrigerant

For a device operating on a thermodynamic cycle, the material and thermophysical properties of the working fluid have a huge impact on the overall performance of the device. In our case, the working fluid is the refrigerant which has to be suitable as it is critical for the efficiency, safety, and environmental impact of refrigeration systems. With increasing concerns about global warming potential, and Ozone layer depletion the choice of refrigerant has become a topic of extensive research in the refrigeration industry.

Other than having low global warming potential and zero ozone depletion potential an ideal refrigerant must have the ability to efficiently absorb and release energy during the refrigeration cycle without undergoing any chemical changes. Moreover, it must also be non-toxic, cost-effective, easily available, and compatible with materials it comes in contact with like metals, plastics, and elastomers.

R-134 a is an HFC refrigerant commonly seen in HVAC applications including domestic refrigerators. It has favorable thermodynamic properties including a relatively high latent heat of vaporization and a low boiling point. These thermodynamic properties enable it to effectively absorb heat from the cooled space and release it to the environment. In addition, it has a low GWP value compared to older refrigerants like chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs). While it does not deplete the ozone layer, it still contributes to climate change when released into the environment. Experimental results of the measurement of thermophysical and transport properties of the refrigerant R-134a reveal that the properties can vary from the literature values from about 1.5% at 251K to 30% at 343 K. (Lavrenchenko, 1992).

CHAPTER 3: METHODOLOGY

This section outlines the sequential steps and methodologies employed to fulfill the project's objectives while adhering to the specified target specifications. Central to the methodology is the comprehensive analysis of cooling load requirements, pivotal for determining the necessary refrigeration capacity and energy consumption of the system. Consideration was given to selecting a suitable compressor and solar panels, designing the heat exchanger, and other accessories.

Target Specifications

The target specifications aimed to create a unit suitable for a significant portion of produce in Pakistan. Initially, the prototype was designed to maintain an appropriate temperature range for fruits and vegetables, with plans to incorporate temperatures for dairy and meat in future upgrades. The decision to opt for a rectangular shape for the container was made to provide a simple structure that would be easy to transport and mount on vehicles. This shape also maximizes the volume to area ratio, allowing for sufficient accommodation of produce. The mass limit for stored produce was set at <1000 kg, considered a compromise between maximum capacity and refrigeration load.

A vapor compression cycle powered by a DC compressor was chosen for the refrigeration system. This compressor would be powered by a 12V DC battery, receiving energy from three solar panels. The panels, featuring hinges for inclination adjustment, are strategically positioned on the top and both longer sides to optimize sunlight exposure. R-134a was nominated as the refrigerant being environmentally friendly and economic, necessitating compatibility with the compressor.

Polyurethane foam was selected for insulation. Widely used in household and industrial refrigerators, this insulation material offers an effective solution for maintaining temperatures.

Table 1: Targetted Specifications

Parameter	Specification
Structure	Rectangular
Power Source	3 Solar Panels
Power Storage	12V Battery
Compressor	DC Compressor
Refrigerant	R-134a
Storage Capacity	1000 kg
Produce	Fruits & Vegetables
Temperature Range	0-5 $^{\circ}$C
Insulation	Polyurethane Foam

Design Process

The process followed for the design of the unit is depicted in the flowchart.

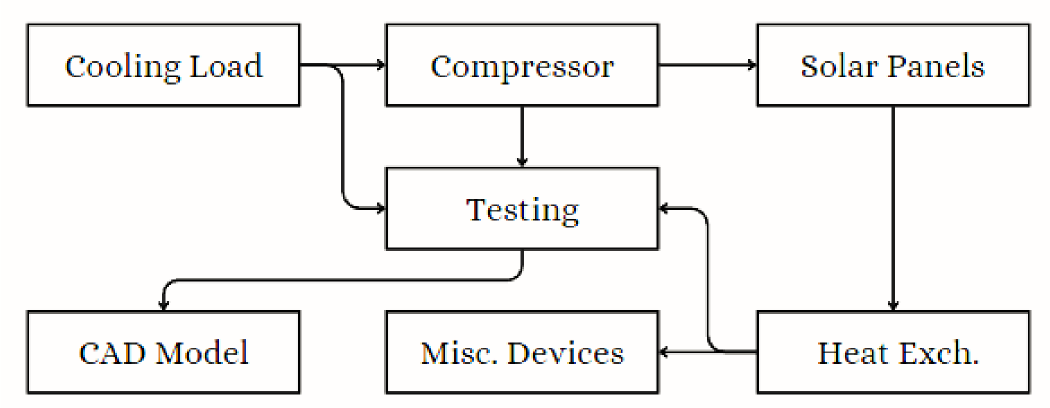

Figure 1: The Design Process

The very first step of the process was to calculate the cooling load for the refrigeration cycle which included various factors which are discussed ahead. The cooling load calculation provided a value for the compressor rating. The compressor was selected based on this value and the selected compressor answered the question of the power requirement for the unit. The solar panels were selected to deliver a surplus of power than the required amount.

At this stage, the refrigeration cycle was designed, and the state values were defined. The next step was to design the evaporators and condensers for the unit, after which other equipment including sensors, thermostat, and capillary tubes were selected.

Throughout the process, different software and online tools were employed to simulate and test the results and design values. Once the testing phase was complete, the CAD model of the unit was developed which concluded the process.

Cooling Load of Refrigerator

The main objective of any cold room is to keep the stored goods at an optimal desired temperature to keep them from being spoiled for as long as possible. For this, a refrigeration system is used to remove the heat from the storage space. The amount of heat that is to be removed is then known as the cooling load or the cooling capacity of the refrigerator. There are several sources of heat inside the cold room and these all contribute as load factors.

Transmission Load:

Transmission loads contribute about 5-10% of the total cooling load. This is basically the heat that enters from the surroundings into the storage space through the walls, roof, floor, doors and windows due to the temperature difference. The mode of heat transfer is via conduction, convection and radiation through the various materials present in the path of the heat transfer.

Therefore, the choice of materials, especially the insulation within walls, affects the magnitude of the heat transfer rate and efficiency. For our design, we have employed 100 mm thick sheets of polyurethane foam insulation sandwiched between stainless steel metal sheets for the walls, roof, floor, and door as well. There are no windows in the present design. The transmission load is calculated by the formula,

$$\dot{Q}_{trans} = UA(T_{out} - T_{in})$$

The overall heat transfer coefficient includes the effect of the individual k-values of constituent materials, steel sheets and polyurethane foam, as well as the convection heat transfer coefficient of air. This is calculated by,

$$U = \frac{1}{1/h_i + x/k + 1/h_o}$$

According to the 2022 ASHRAE Handbook—Refrigeration Chapter 24, the value of 9.1 is used for h_i and h_o for still air and 34 is used for wind speed of 25 km/h. The still air approximation is considered for inside air and the wind approximation for outside air for the worst-case scenario. It also says that the effect of solar radiation can be accounted for by adding to the normal temperature according to the orientation of the walls with respect to the sun and the color and materials of the components. The exact values are mentioned in Table 3 in the Handbook.

Product Load:

Product load amounts to nearly 55-75%, forming the bulk of the total cooling load. This refers to the heat that needs to be removed from the fresh (or other) produce to bring it down from its existing temperature to the desired cool temperature. The internal temperature (and RH) varies according to the produce and is set according to the guidelines set by the ASHRAE Handbook—Refrigeration in Table 1 of Chapter 21. Sometimes, freshly harvested produce at field temperatures need to be cooled, which results in a large temperature difference thus the high value of this load factor.

The product load is calculated as follows,

$$\dot{Q}_{produce} = 1000\, mc_p(T_{enter} -)/3600t$$

The specific heat capacity of various commodities is obtained from Table 3, Chapter 19 ASHRAE. The mass of the produce is determined using the internal volume of the refrigerated space while keeping a factor of 30% as the void volume accounting for the air spaces and packing conditions. Therefore, mass is given by,

$$m = 0.7\rho V \ \ and, \qquad \rho = \frac{1}{\sum x_i/\rho_i}$$

Where,

x_i and ρ_i are given in Table 1 Chapter 19, 2022 ASHRAE Handbook—Refrigeration.

Respiration Load:

Respiration of the fruits and vegetables also release heat and add about 10-20% to the total cooling load. This load is calculated by Equation 41 of Chapter 19 given by the ASHRAE Handbook,

$$\dot{Q}_{resp} = m\frac{10.7f}{3600}\left(\frac{9T_{in}}{5} + 32\right)^{g}$$

Where, f and g are respiration coefficients for commodities given in Table 8 Chap 19 ASHRAE.

Equipment Load

This factor generally accounts for about 1-10% of the total load, it is the heat generated by the running equipment such as evaporator fans, lights etc. inside the containers. For this design, the only equipment used inside the compartment was lights therefore the heat generated by lighting is calculated as for 'n' number of lights,

$$\dot{Q}_{equip} = {nt_{light}\dot{Q}_{light}}/{t}$$

Infiltration Load

This factor contributes 1-10% to the total load. It refers to the heat added to the refrigerated space by warmer air that enters into the compartment through doors, windows or other openings. It is measured using the equation,

$$\dot{Q}_{infil} = {r_c V_{in} c_{vol} (T_{out} - T_{in})}/{3600t}$$

Cooling Load Software Simulation

As with any design process, manual calculations and results were to be verified by simulating the same model on computer software. This ensures that the results obtained are accurate and can be used for further analysis, finalization of a component, and procurement of required materials and equipment.

INTARCON software has been used for the simulation of the cooling load for the cold room design. This software accounts for all possible factors that contribute to the cooling load. The user must specify the type of cold room with the intended application, its internal dimensions, desired internal and ambient temperature. Next, it prompts the user to choose the product type ranging from general fruits and vegetables and other specific commodities, along with their respiration rate, packaging type, total load, daily turnover, and other thermal properties. The location, which includes altitude, RH, daily temperatures and whether it is placed in sun, shade or indoors, has to be specified to as well as daily insolation and surface finish of the container. The insulation type, thickness and areas of all surfaces are to be added. It accounts for ventilation through doors and other thermal loads due to fans, lighting, and people as well.

Refrigeration Compressor Selection:

The compressor is a very critical component of any refrigeration cycle. It draws in low-pressure and low-temperature vapors of the refrigerant from the evaporator and then increases its pressure and temperature greatly. This step is vital as it ensures that the refrigerant absorbs heat from the refrigerated space at a suitable rate as mandated by the design size of the system and the daily run time. The compressor initially runs continuously to remove the field heat or the product heat as well as the heat added from the infiltration air, while simultaneously heat added through walls, equipment and respiration, to achieve the desired internal set point temperature. Once this is achieved, the compressor then attains a steady state condition at which it only removes the heat being transmitted from the outside. The following factors had to be considered while selecting a suitable compressor:

1. Power Capacity

The compressor rating is decided by the cooling load of the cold room. This cooling is determined by considering various factors including temperatures, insulation, stored commodity, room size etc. and the method to find this is outlined already. The capacity of the compressor in Watts should be sufficient for the initial compressor phase until a steady state is achieved.

2. Operating Conditions

The desired internal temperature range and the ambient environment determine the operating conditions of the compressor. These are present the compressor datasheets as a range of evaporating and condensing temperatures in which the compressor is operational. The compressor pressure ratios and pressure lines are considered for the desired temperature ranges.

3. Refrigerant Type

Various compressors work with various refrigerants, some even operate with multiple refrigerant types. It is important to ensure that the selected compressor is compatible with the desired refrigerant type and that it also meets the environmental standards set by international bodies.

4. Size Constraint

The size of the compressor is also very important. It should be able to fit within the limited space available along with the cold compartment and not increase the weight too much especially since the desired product is intended to be one complete integrated unit with the option of portability.

5. Energy Efficiency

The efficiency of the compressor is measured by its COP, the higher COP compressor is desired since it requires low power input to achieve the same cooling rate inside the refrigerator. It is also favorable to the environment and helps reduce the operating costs.

Solar Panel Selection

The refrigeration unit, like any electrical system, needs a power source. The solar panels described in the target specifications are the primary power source for this unit. The sizing of the solar panels is a crucial step. The larger the solar panels are, the larger the unit is. A larger unit requires more cooling, consequently increasing the power requirement from the panels, so a balance is to be maintained between the panel size and the cooling load. The compressor power requirement is the main component of the total load, so the collective power output of the three panels is to be greater than this requirement, in order to run the compressor and the miscellaneous equipment while charging the battery simultaneously. The market survey shows that certain panels, which have suitable power output have an inadequate aspect ratio, and so this factor is to be considered as well.

Heat Exchangers Design

The heat exchangers involved in the refrigeration system are evaporator and condenser. The evaporator has low temperature and pressure refrigerant that absorbs heat from the refrigerated space and causing cooling inside whereas the condenser contains high temperature and pressure refrigerant that rejects heat to the surroundings. The net effect of these two is the power delivered by the compressor.

The rate of heat absorption and rejection is determined by three factors:

1. The overall heat transfer coefficient, U, of the HE coils. It is determined from the material of the tubing i.e. the conduction effect, as well as the convection effects on the inner and outer surface. The U-value is derived from experimental data for various applications, materials and refrigerants.
2. The temperature difference that exists between the inlet and outlet of the refrigerant as well as the air being cooled (or heated in case of condenser).
3. The total heat transfer area of the entire heat exchanger from the inlet to outlet. The greater the surface area the higher the heat transfer rate.

Refrigerant State Points:

For the current system, the material of the HE coils was already set i.e. copper tubes. Next, the state point conditions of the refrigerant throughout the refrigeration cycle had to be specified in order to determine the operating conditions of the refrigerant at HEs inlets and outlets, those of air were already set. Since the compressor was already selected, power, COP, displacement (cc), compressor inlet temperature (evaporating temperature) and RPM were extracted from the datasheet. Using the evaporating temperature in conjunction with R-134a property tables, the specific volume (v) of the refrigerant in compressor is determined. Then, the mass flow rate (kg/s) of the refrigerant is,

$$\dot{m} = \frac{RPM \times cc \times 10^3}{60 \times v}$$

This mass flow rate is then used together with the COP, compressor work, and R-134a property tables to specify the temperature at each point in the cycle.

Heat Transfer Area:

The main objective was to calculate the heat transfer area in order to determine the size of the HE or the length of the copper piping that would be required to achieve the desired heat transfer rate. Now that the temperature at both inlets and outlets are determined, the LMTD method can be used to calculate the areas,

$$\Delta T_{lm} = \frac{\Delta T_1 - \Delta T_2}{\ln(\Delta T_1/\Delta T_2)} \quad where, \quad \Delta T_1 = T_{\mathrm{h,in}} - T_{\mathrm{c,out}} \quad and, \quad \Delta T_2 = T_{\mathrm{h,out}} - T_{\mathrm{c,in}}$$

$$A_{evap} = \frac{\dot{Q}_{absorbed}}{UF\Delta T_{lm,evap}} \quad and, \quad A_{cond} = \frac{\dot{Q}_{rejected}}{UF\Delta T_{lm,cond}}$$

The evaporator and condenser areas can be calculated using these equations. According to literature the condenser area should be approximately twice that of the evaporator area in order to ensure efficient operation. For the length of copper piping, the area was simply divided by circumference of the pipe i.e. π*d where d is the external diameter of the pipe.

Throttling Device Selection

Throttling devices are a crucial component of every refrigeration system. It throttles the high-pressure fluid exiting the condenser to a low pressure and temperature liquid-gas mixture which vaporizes in the evaporator by absorbing heat. Another function of the expansion device is to control the flow of the refrigerant going to the evaporator. Ideally, the mass flow rate of refrigerant in the system should be proportional to the cooling load, so the flow must be controlled in such a way that only superheated vapor leaves the evaporator. The device should minimize the energy requirement and satisfy the temperature and cooling load criterion. Most domestic refrigerators use a thermostatic expansion valve, but industrial refrigerators have capillary tubes which have a fixed area. The selected throttling device for this system should be inexpensive and compatible with the compressor and refrigerant.

Thermostat Selection

A thermostat is used to monitor the temperature inside the unit and control the compressor in such a way that the set value of temperature is achieved. The thermostat should be compatible with the power supply and have a temperature sensor within the range of the cabin temperatures. The sensor should also be accurate enough to monitor the exact temperature.

CHAPTER 4: RESULTS and DISCUSSIONS

Unit Structure

After running several iterations to achieve a balance between the solar panel power and cooling load, the final dimensions were selected. Each wall consists of various layers to offer structural integrity, insulation and accommodation of equipment. The main wall is a thick layer of polyurethane sandwiched between two steel sheets. Inside this, the copper tubes of the evaporator are placed which have a diameter of 0.3m. To seal the structure, another steel sheet is placed after the tubes. Each wall has a total thickness of 0.1318m.

Each of these layers resists heat transfer with the environment. The insulation value of every layer is considered in the cooling load calculations.

Table 2: Finalized Dimensions of the Refrigerator Unit.

Parameter	Value (SI Units)
External Dimensions of Unit	1.885 x 1.208 x 1.208
External Volume of Unit	2.751
Internal Dimensions of Compartment	1.431 x 0.924 x 0.966
Internal Volume of Compartment	1.278
Internal Surface Area of Compartment	7.196
External Dimensions of Compartment	1.6338 x 1.1268 x 1.168
External Volume of Compartment	2.15
External Surface Area of Compartment	10.131

Cooling Load Calculation

For the analysis, an ambient temperature of 25 °C, internal 4 °C and runtime of 18 hours was used. First, universal heat transfer coefficient was evaluated which is same for all the surfaces.

$$U = \frac{1}{1/9.1 + 2(0.0006/14.3) + 0.1/0.03 + 1/34} = 0.288\, W/m^2.K$$

For the transmission load, the area of each wall, roof and floor were considered separately and the temperature difference was adjusted to include the effect of solar radiation by adding a specific amount depending on orientation.

Table 3: Heat Transmission Surfaces and Load Fraction.

Surface	Area (m^2)	Sun Allowance [a] (°C)	Heat Transmission (W)
North Wall	1.316	-	7.959
South Wall	1.316	+2	8.717
East Wall	1.908	+3	13.19
West Wall	1.908	+3	13.19
Flat Roof	1.841	+5	13.78
Floor	1.841	-	11.13
Total	**10.13**		**67.97**

[a] These values are obtained from Table 3, Chapter 24 of 2022 ASHRAE Handbook—Refrigeration.

The product load and respiration heat were evaluated for multiple types of commodities, their respective masses and densities were measured using the equations mention in the Product Load section of Methodology Chapter.

Table 4: Product and Respiration Load of Various Commodities

Commodity Type	Density (kg/m^3)	Mass (kg)	Respiration Load (W)	Product Load (W)
Tomato	630	563.45	11.044	726.75
Apricots	650	581.34	13.539	693.30
Beet	700	626.06	16.288	764.89
Broccoli	560	500.85	11.440	624.90
Plums	610	545.56	7.5871	659.48
Average	630	563.45	11.980	693.86

As mentioned previously, only lighting equipment was used inside the compartment. A single LED light was used with a power consumption of 50 W and running for 1 hour per day during loading or unloading. Therefore, we have equipment load as,

$$\dot{Q}_{equip} = {}^{1 \times 1 \times 50}/_{18} = 2.778\,W$$

The volumetric heat capacity of air is 1200 J/m^3.°C and the number of volume changes per day was taken as 2.3, this gives infiltration load equal to,

$$\dot{Q}_{infil} = {}^{2.5 \times 1.28 \times 1200 \times (25-4)}/_{3600 \times 18} = 1.242\,W$$

INTARCON Cold Room Simulation

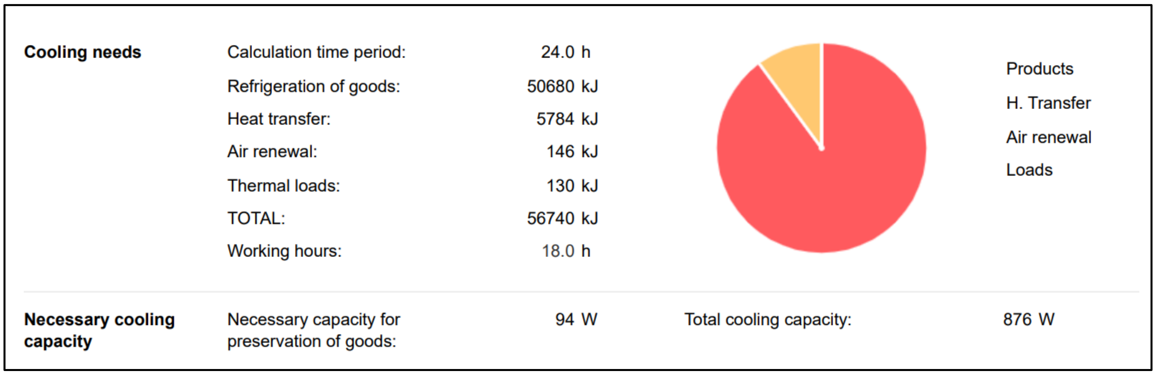

Figure 2: Results report from INTARCON Cold Room simulation.

The following table shows the final comparison between the results obtained from the simulation and the manual calculations done using the equations in the 3rd chapter.

Table 5: Final Load Fractions and Total Cooling Capacity of Refrigerator.

	Manual Excel Calculations		INTARCON Simulation	
	Load (W)	**Percentage (%)**	**Load (W)**	**Percentage (%)**
Transmission	67.97	8.74	89.26	10.19
Product	693.86	89.20	782.10	89.28
Respiration	11.98	1.54		
Equipment	2.778	0.36	2.01	0.23
Infiltration	1.242	0.16	2.25	0.26
Total Capacity	**777.83**	**100**	**876**	**100**

It can be seen that both methods had quite close results. The product load of the simulation is notably higher as the specific heat for the product in the software is higher than that of the manual calculation and it also accounted for relative humidity of air. The transmission load is also slightly higher since the software accounts for solar radiation by the daily insolation of solar radiation of 5 kWh/m^2 where as in manual calculations only an addition was made to the normal temperature difference through each surface. The difference was accounted for by adding a 15% allowance for constraints and other basic assumptions made.

Selection of Compressor

For the choice of the compressor refrigerant R-134a and DC power constraints were kept in mind. Next the necessary rating of the compressor was determined using the cooling capacity of the system. This was done by applying 15% allowance to the total load,

$$\text{Desired Cooling Capacity} = 777.83(1 + 0.15) \approx 895\, W$$

Thus, a compressor having a cooling capacity of at least 895 W was needed with the actual power input depending on the COP. After survey three main problems were faced:

1. A compressor with such a high-power rating was not available locally even though sellers in multiple cities were contacted as well as manufacturers of cold rooms and reefer containers. Importing from international increases cost and delivery time.
2. Larger compressors rarely run on DC supply and that was one of the main design constraints. An AC compressor would require a smart solar inverter for the desired system which would greatly increase the cost of the product and cross budget.
3. High cooling capacity meant a larger and heavier compressor which would not only increase the overall weight but space for refrigeration and auxiliary equipment was also limited to a slim cabinet at the back end of the container behind the refrigerated compartment.

All these issues were addressed by employing an innovated system containing multiple identical but smaller compressors working simultaneously to achieve the desired cooling effect. The compressor that accounted for all the requirements was selected and it was the SECOP BD80F Direct Current Compressor. It was seen that four units of this compressor would be sufficient to meet the needs of the refrigerator for optimal cooling and feasible cost and space requirements.

Table 6: SECOP BD80F Specifications.

Power Supply V	Evaporating Temperature °C	Weight kg	Compressor Displacement cm^3	COP	Compressor Work	Cooling Capacity
				@ -5°C Evaporating Temp, 2500 RPM		
12/24	-30 to -5	4.4	3	1.9	91.9 W	174 W

Solar Panel Selection

According to the specifications of the compressor, at an evaporating temperature of -5°C, the compressor work is 91.9W. For the four compressors, the total power requirement would be 367.6W. In order to run these compressors and the other equipment while charging the battery simultaneously, the panels should have at least 700W power output.

After an extensive market survey, the selected panels were the Canadian Solar HiKu Poly Perc Module with a power rating of 325-350W each. This makes the total power output around 1000W which is more than enough for our requirements. The dimensions of these panels are 70 by 40 inches. This is perfectly matched to the unit dimensions which was an initial constraint. The selected module has 24% higher power than conventional modules and also offers better shading tolerance, which means that it produces power even when sunlight is not directly incident on it. For power storage, a 12V DC battery was selected from a local manufacturer.

Design and Analysis of Heat Exchangers

With the data of compressor available, the next step was to calculate the necessary area for the heat transfer in evaporator and condenser. The area was calculated for the minimum attainable temperature in the refrigerated according to the targeted specifications which was 0 °C. To attain this an evaporating temperature of -5 °C and 2500 compressor RPM was used together with R-134a property tables to find the mass flow rate. Consequently, the state at each stage in the refrigerator was defined.

$$\dot{m} = \frac{2500 \times 3 \times 10^{-6}}{60 \times 0.0798} = 0.00157\ kg/s$$

$$r_c = \frac{1600}{243.65} = 6.57$$

Table 7: R-134a States at Each Stage in Refrigeration Cycle.

	Temperature (°C)	**Pressure (kPa)**	**Quality (x)**	**Enthalpy (kJ/kg)**	**Entropy (kJ/kg.K)**	**Specific Volume (m^3/kg)**
Evaporator Inlet	-5	243.65	0.45	136.42	0.5201	0.03641
Compressor Inlet	-5	243.65	1	247.51	0.9343	0.0798
Compressor Outlet	78.7	1600	>1	306.18	0.9875	0.0142
Condenser Outlet	58	1600	0	136.42	0.47911	0.0009

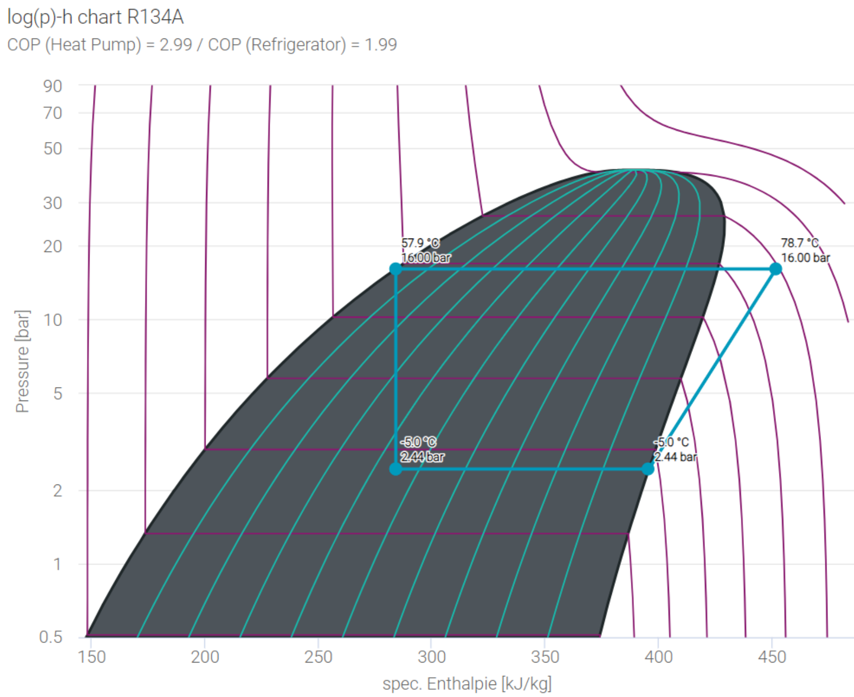

Figure 3: Pressure and enthalpy diagram of the refrigeration process.

In the case of the evaporator, the refrigerant temperature theoretically stays constant as it is a phase change process i.e. -5 °C while the temperature of the air inside the refrigerator was to be reduced from 25 °C to 0 °C.

As for the condenser, the refrigerant temperature decreases from superheated state to saturation temperature at the higher pressure this was calculated to be 78.7 °C to 58 °C while the temperature of the outside air increases approximately about 1-2 degrees from ambient which is from 25 °C to 27 °C. The rate of heat rejection from the condenser is the sum of cooling capacity and compressor work, $\dot{Q}_{rejected} = 174 + 91.9 = 265.9\,W$

The overall heat transfer coefficient of the copper coils, refrigerant in pipes and air outside, was derived from experimental data in literature i.e. $U = 11.16\ W/m^2K$. And the correction factor for the cross flow, refrigerant unmixed and air mixed, heat exchanger was $F = 0.6$. Thus, the overall heat transfer areas for the HEs were obtained.

Table 8: Final Design of Evaporator and Condenser.

	R-134a ℃		Air ℃		ΔT_{lm}	Heat Transfer	Area	Length
	in	**out**	**in**	**out**	**℃**	**W**	**m^2**	**m**
Evaporator	-5	-5	25	0	27.21	174	2.55	27.02
Condenser	78.7	58	25	27	-21.81	265.9	4.86	57.52

As it can be seen from the table, the condenser area was approximately twice that of the evaporator which agrees with theory,

$$A_{cond} = 4.86 \approx 2 \times 2.55 = 5.09\ m^2$$

Throttling Device Selection

The most attractive option for the throttling device were the thermostatic expansion valve and the capillary tube. The capillary tube was selected because of low cost, having no dynamic parts and ideal compatibility with hermetic compressors. A capillary tube uses friction offered by the tube walls to induce pressure drop. The velocity increase in the tube also causes pressure drop.

Compressor Control Kits

A control module has been integrated with each compressor to overlook the voltage level going to the motor. This module allowed us to add fans and LEDs to the circuit along with a thermostat which can be used to control the compressor rpm, consequently controlling the cooling. Without a thermostat the compressor would run at full rpm. The power to the compressor goes through this module. Circuit breakers have also been added in each loop as a safety measure.

Electronic Controller

Another component selected for the system is an MPPT electronic controller which draws power from the solar panels and directs it to the unit or the battery according to power requirements which depend on the incident sunlight and cooling load at the instant. The controller also regulates the voltage to the desired 12V level.

Filter drier

After each condenser, a filter drier has been added to each closed cycle. This filter traps moisture and contaminants to prevent corrosion, thereby causing a slight pressure and temperature drop.

Condenser Fans

To facilitate heat transfer and increase the efficiency of the refrigeration cycle, forced convection on the condenser was implement. A 12V DC fan was added to induce air flow through each of the four condensers. The fans draw power from the controller of their respective compressors.

Batteries

Two batteries were placed in the unit to store power and run the system during hours of low sunlight. Each battery has a capacity 165AH and has been sourced from Daewoo.

Miscellaneous Equipment

The door lock attached to the unit is a push and pull latch which is typically used in cold storage systems. The unit has been mounted on 6” rubber wheels, two of which have locking mechanisms to prevent the unit from moving in an unbalanced position. The equipment cabinet has two doors, each with a lock and key, to secure access to the equipment. To aid airflow to the condenser, small horizontal slots have been made in both doors of the equipment cabinet.

CAD Model

The final step of the design process was to fabricate a virtual model of the unit using Computer Aided Design. SolidWorks was used to model this unit.

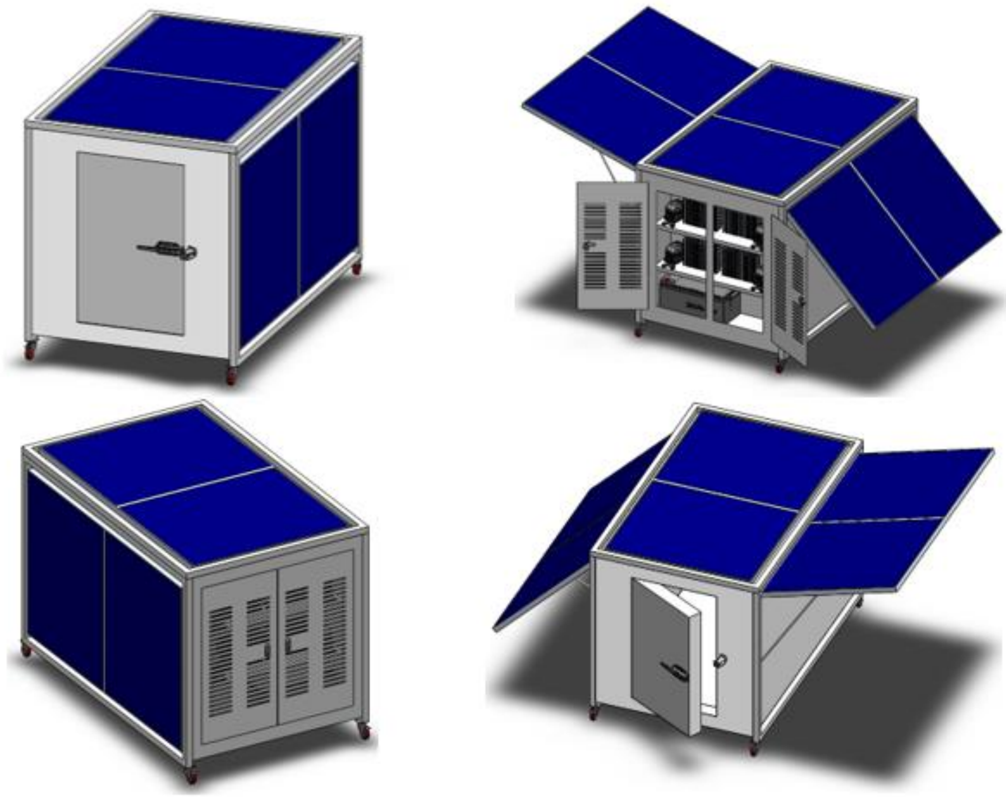

Figure 4: CAD model

Final Prototype

Figure 5: Pictures of prototype.

Performance Evaluation

After the fabrication of the unit, the testing phase began, which included various procedures to observe how well the systems were working and whether they were achieving the objectives set at the beginning. This step was necessary to decide upon the reliability and effectiveness of the proposed solution. For the project to be a success, the unit would have to remove heat from the cabin and prevent the test produce from being spoiled. The main parameters being monitored were the temperature gains and losses in different conditions, while also monitoring spoilage at the unit state being achieved.

The main aims of this testing cycle are discussed ahead.

1. Determine cooling efficiency under different environmental conditions. This would quantify how well the unit would perform at different ambient temperatures and solar energy levels. If implemented, the unit would have to face a wide range of external conditions. Observing the temperatures on the inside and outside, and the time taken to reach a suitable state should provide enough information to make a conclusion. This aim evaluates the performance of the designed refrigeration system.
2. Monitoring the rate of temperature decay once the desired state has been achieved and the unit is shut. This would help evaluate the effectiveness of the insulation used in the walls. A high decay rate would mean that the unit would not be a feasible solution even if the refrigeration cycle works perfectly. The decay rate has to be observed under different external conditions to draw a satisfactory result.
3. Assessing the reliability and robustness in sustaining a low temperature over long durations of time. This would show that the unit is capable of being a suitable remote and off-grid solution.

To ensure sufficient power supply for uninterrupted running of the refrigerator, the solar panels were strategically positioned and adjusted throughout the testing period. The panels on either sides were adjusted for optimum sun tracking and enhancing exposed area and energy absorption.

The readings were recording via a networks of various temperature and humidity sensors placed inside and outside the cold storage. These sensors were used to obtain data of ambient and internal air temperature and relative humidity and also the temperature of each of the four evaporator plates. This enabled monitoring of fluctuations in external and internal environment to help holistically understand and analyze system performance.

The testing was carried out in short-term and long cycles. And in two phases to analyze two metrics as mentioned in the aims. Temperature readings were recorded at regular intervals for a four hour testing duration as well as a 24-hour testing duration. The former was to analyze a typical daylight cycle while the latter simulated overnight storage of produce in actual scenarios.

Similar tests were carried out on the short term cycle for the second phase that is to observe temperature rise inside the compartment after the cooling system is turned off. This was done to evaluate the robustness and integrity of the cold storage insulation.

All the tests were carried out on various days with differed environmental conditions to obtain sufficient data for the performance based on the metrics stated earlier. Graphical representations of temperature trends facilitated the visualization of system performance and provided insights into the efficacy of the cold storage solution.

Table 9: Cooling data of on a prticular day for a four hour testing cycle.

Time	T_i	T_o	Φ_i	Φ_o
12:27	23.1	24.7	55	30
13:06	22.6	26	60	27
13:20	22.4	26.1	60	27
13:35	22	26.4	58	27
13:50	21.5	26.7	56	26
14:00	21.2	26.8	55	27
14:17	20.6	26.7	53	27
14:30	20.2	27.1	52	27
14:45	19.7	27	54	27
15:00	19.2	27	53	27
15:15	18.7	26.8	52	27
15:30	18.4	27.1	52	26
15:45	17.9	27	51	27
16:00	17.6	26.9	51	27
16:15	17.3	26.7	51	27
16:30	17.1	26.5	51	27

Table 10: Decay data on a particule day for a two hour testing cycle.

Time	14:53	15:06	15:15	15:31	15:46	16:02	16:17	16:33	16:48
T_i	14.3	14.9	15.6	16.3	17.4	18.3	18.9	19.3	19.6

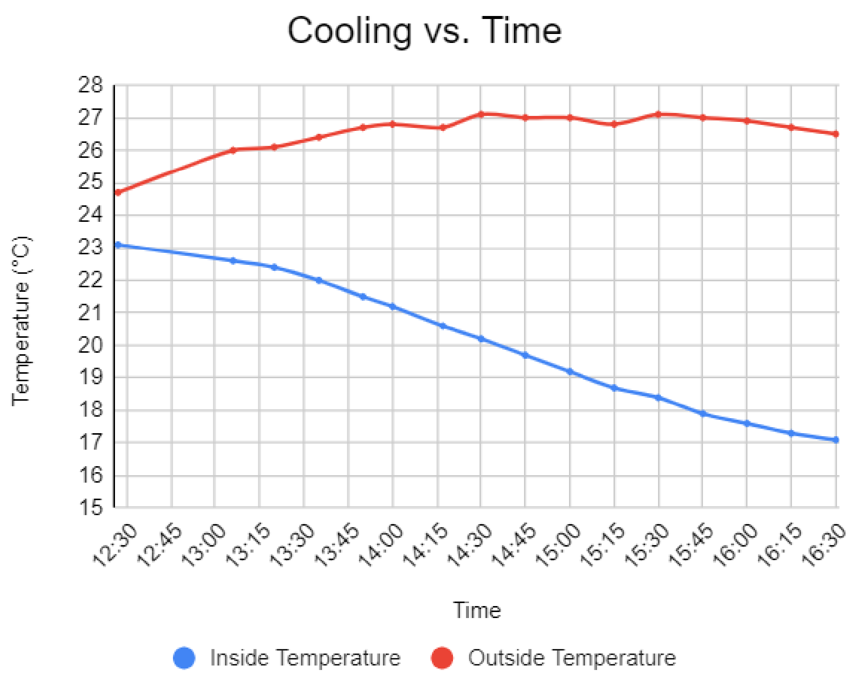

Figure 6: Graphical representation of temperature decrease with time on a particular day.

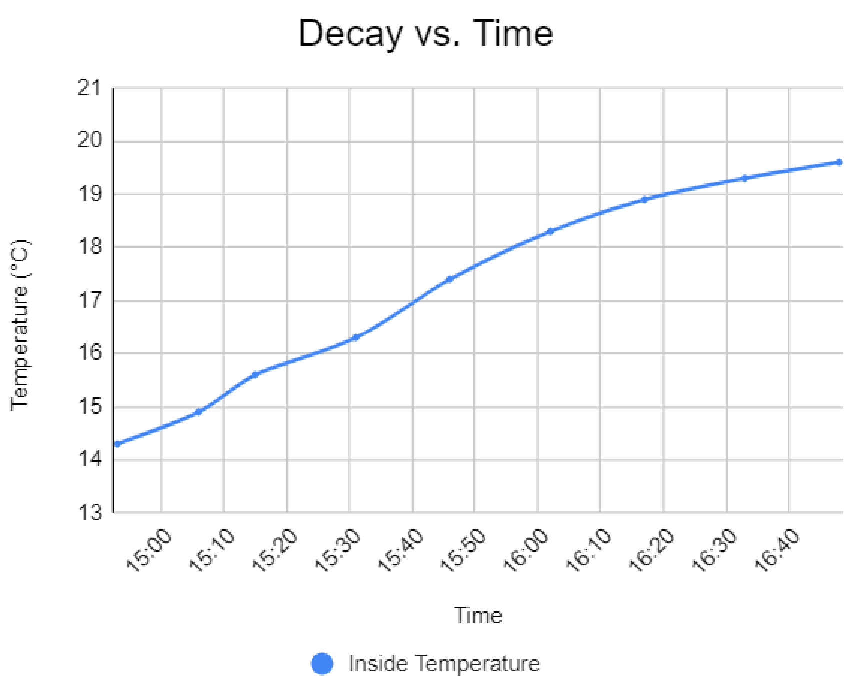

Figure 7: Graphical representation of temperature rise with time on a particular day.

The cooling data reveals a consistent decrease in internal temperature over the course of the testing period, indicative of the cooling effect produced by the refrigeration system. Despite fluctuations in ambient temperature and humidity, the internal temperature steadily declines, demonstrating the system's ability to maintain desired cooling levels. The observed temperature drop is within the expected range, aligning with the project's objective of preserving perishable goods by creating a conducive storage environment.

Furthermore, the data for also illustrates a gradual increase in internal temperature after the cooling system is turned off, reflecting the decay phase of the cold storage process. Rapid temperature increase during the decay phase may suggest potential limitations in insulation or thermal retention capabilities of the cold storage compartment. A thorough analysis of the temperature rise dynamics can inform improvements in insulation materials and design strategies to enhance the system's resilience to temperature fluctuations.

Bill of Materials

After the procurement of all the equipment, the bill of materials was obtained. The total cost of the unit was well under the allocated budget, and so the project was financially successful. The manufacturing costs are included in the pricing.

Table 11: Bill of Materials

Item	Quantity	Unit Price (PKR)	Total Price (PKR)
Solar Panel	3	35,000	105,000
DC Compressor	4	41,300	165,200
Condenser Fan	4	6,000	24,000
Evaporator System	4	15,000	60,000

Piping	80ft	250	20,000
Refrigerant (R-134a)	~1.2kg	10,000	10,000
Thermostat & Wiring	1	5,000	5,000
Filter Dryer	4	2,000	8,000
Insulation	1	50,000	50,000
Hinges	2	4,000	8,000
ating and Paint	1	25,000	25,000
Metal Structure	1	150,000	150,000
Throttling Device	-	5,000	5,000
Miscellaneous	-	94,000	94,000
Grand Total			**725,000**

CHAPTER 5: CONCLUSION and RECOMMENDATIONS

In conclusion, this report highlights the progress so far made in the development of the Portable Solar Refrigerator with a Backup Battery, and how the project aims to provide a sustainable solution for inadequate cold storage and related problems faced by farmers by implementing solar-powered refrigeration.

The comprehensive exploration of the problem statement, project objectives, and literature review laid a foundation for understanding and development of the project. The design process includes considerations like Cooling Load Calculations, Compressor and Solar Plate Selection, Heat Exchanger Design, and Throttling Device and Thermostat Selection. Cooling Load of any unit is composed of multiple factors like Infiltration, Transmission Load, Respiration Heat, Field Heat etc., all these factors play a major role while determining the load of any refrigeration unit.

The final dimensions of the unit were selected after performing several iterations to balance the cooling load and solar power. Multiple insulation layers were added to each wall to provide structural integrity and to minimize the heat loss. The primary wall consists of a thick layer of PU Foam sandwiched between two layers of steel sheets. Inside this, 0.3m diameter copper tubes for the evaporator were placed, followed by another steel sheet to seal the structure.

We opted for a DC Compressor with refrigerant R-134a. The necessary compressor rating was determined based on the cooling capacity of the system with a 15% allowance applied, which led to a desired cooling capacity of 895 W, but locally made DC Compressors of such rating are scarce. Using an AC Compressor or importing a DC Compressor would escalate costs. We also faced space constraints while tackling a cooling load of such high magnitude.

Thus, to address these challenges, we employed multiple identical but smaller compressors to achieve the desired cooling effect. After consideration, SECOP BD80F DC Compressor was chosen. Four units of this compressor were determined to be sufficient for our needs.

Based on the compressor specifications, the total power requirement at an evaporating temperature of -5^{0}C is 367.6W, and to accommodate these compressors and other equipment, solar panels with at least 700W power output were required. The Canadian Solar HiKu Poly Perc Module was selected with each panel between 325-350 W. For Power Storage a 12V DC Battery from a local manufacturer was chosen.

For throttling we opted for capillary tubes as they are inexpensive, they don't have any dynamic parts, and are compatible with hermetic compressors. For temperature measurement we opted for a thermostat. Moreover, an electronic controller was chosen to power distribution from solar panels to the compressors and the battery.

After all this equipment selection, the total cost of the unit came out to be PKR 725,000. The report documents our progress so far. Further research can be done to improve the unit's insulation, in the areas of smart energy management, cold storage optimization, innovative material etc., to improve the cooling load, thereby making the project more sustainable and feasible.

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