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Solar Refrigeration System for Large Scale Horticulture Farmers

BY

Mutara, Tadiwanashe. M

B1852774

SUPERVISOR: Dr. Muchuweni

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APPROVAL FORM

The undersigned certify that they have read and recommended to Bindura University of Science Education for acceptance: A research submitted in partial fulfilment of the requirements for the BSc Physics with specialisation in Environmental physics and energy resources,

Supervisor: Date: 21 December 2022

Programme Coordinator: …………

Date…………………………

RELEASE FORM

NAME OF AUTHOR: TADIWANASHE M MUTARA

REGISTRATION NUMBER: B1852774

TITLE OF PROJECT: SOLAR REFRIGERATION SYSTEM FOR LARGE SCALE HORTICULTURE FARMERS

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I, Tadiwanashe M. Mutara do declare that everything that appears in this project is a result of my own personal work and effort. Any assistance whether material or conceptual, that I have incorporated in my work has been lawfully obtained and is appropriately acknowledged in the following research project.

Signature:  Date: 21 December 2022

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DEDICATION

Dedicated to my parents, Mr. and Mrs. Mutara.

ABSTRACT

A refrigeration system, in general, involves the process of cooling, and it entails removing heat and disposing of it at a higher temperature and it requires installation of refrigeration equipment. The goal of the research was to create a solar-powered refrigeration system that would be used in Zimbabwe's agriculture sector, and since horticulture is a subsector of agriculture, the researcher implemented the system to horticulture farmers. Although some efforts were made to improve agricultural production and reduce the amount of energy withdrawn from the national grid, the need to reduce the amount of energy withdrawn from the grid for refrigeration in Zimbabwe was still lacking. The primary research goals were to develop and design a refrigerator or cold room used to keep horticulture products fresh for a longer period of time, as well as to evaluate the system. The researcher went on to study some software used in simulation of the refrigeration system and the solar array as part of the research project. The methodology focuses on how the current refrigeration cycles and their effect on the system's coefficient of performance that are currently being used to build cooling. However, the system proved to be financially feasible given the country's current inflation on the day the research was authored.

LIST OF ABBREVIATIONS

ANOVA	Analysis of Variance
BOQ	Bill of Quantities
CCHP	Combined Cooling, Heating and Power generation
COP	Coefficient of Performance
DHW	Domestic Hot Water
NZEB	Nearly Zero Energy Buildings
ORC	Organic Rankine Cycle
PV	Photovoltaic
PVsyst	Photovoltaic System Simulation
PCM	Phase Change Materials
SAR	Solar Absorption Refrigeration
SERS	The Solar-driven Ejector Refrigeration System
TRNSYS	Transient Systems Simulation Program

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CHAPTER 1: INTRODUCTION

1.0 Introduction

Electricity generation is the leading cause of industrial air pollution in the country. Most of our electricity comes from coal, gas and other non-renewable power plants. Producing energy from these resources takes a huge toll on our environment, polluting the air, land and also, they are limited. As a result, energy crisis is of major concern since the limited natural resources that are used to power industrial society are diminishing as the global energy demand rises. These natural resources are in limited supply. They occur naturally, and it can take hundreds of thousands of years to replenish the stores. Energy supplied to refrigeration system across the globe has a significant importance. Preservation of perishable products, especially flowers, fruits, meat and fish cannot be insured without refrigeration. These products are required to be stored in low temperatures because cold temperatures slow the progress of biochemical, physical and microbiological processes and prevents further chemical reactions. Therefore, this chapter covers the background, problem statement, objectives, research questions, significance of the study, delimitations, limitations, assumptions and definition of key terms.

1.1 Background

According to Kukreja (2017), an energy crisis is any significant bottleneck in the supply of energy resources to an economy. In literature, it often refers to one of the energy sources used at a certain time and place, in particular, those that supply national electricity grids or those used as fuel. Industrial development and population growth have led to a surge in the global demand for energy in recent years. As a result, the best way to sum up the reality of the energy crisis is a growing demand on limited resources, which may lead to the eventually running out of the resource. In developing countries, such as Zimbabwe, energy crisis is a result of many different strains on our natural resources, not just one. There is a strain on fossil fuels, such as oil, gas, and coal, due to over consumption, which then, in turn, can put a strain on our water and oxygen resources by causing pollution. There is also the aging of infrastructure of power generating equipment, which is yet another reason for energy shortage. Most of the energy-producing firms keep on using outdated equipment that restricts the production of energy. It is the responsibility of utilities to keep on upgrading the infrastructure and set a high standard of performance. Carson et al. (2018) state that electricity production in southern Africa continues to fall short of the level needed to support both household and commercial needs. It is widely agreed that regional cooperation and integration in energy planning and development could help to tackle this issue and unlock the potential for economic development in Southern Africa.

Zimbabwe is part of Southern African Development Community (SADC) countries whose electricity needs are basically met by a monopoly electricity provider. In Zimbabwe, Zimbabwe Power Company (ZPC) is the company which provides electricity, and has however been facing challenges in meeting the daily projected electricity requirements of 2500MW of electricity as its power stations can only manage to produce less than half the current demand, which lead to a power deficit that is being supplied through imports from neighbouring countries Zimbabwe Power Company (2022). The power deficit comes at a period when less than half of the country's population has access to electricity, and when the manufacturing industry running at its record low, which is 20% of the full industry capacity as most industries eventually came to a halt due to foreign currency shortages and inflation. This has led to the Zimbabwe energy regulatory authority to call for independent power producers to come and invest in the energy sector of Zimbabwe and producing power for resale to the national power supplier at a fixed tariff price.

The shortage in electricity in the country has hindered some sectors in the economy, such as the agriculture, mining and tourism industry. According to Pawlak and Kolodziejczak (2020), ensuring food security has become an issue of key importance to countries with different degrees of economic development, while the agricultural sector plays a strategic role in improving food availability. However, developing countries are facing challenges in maintaining food security, which has a high share of agriculture in their Gross Domestic Product (GDP), and this is due to the lack of or outdated infrastructure and technology, and shortage of electricity in the countries. Food and Agriculture Organization (FAO) (2000), explains agriculture as an energy conversion process, namely the conversion of solar energy through photosynthesis to food energy for humans and feed for animals. Modern agriculture requires an energy input at all stages of agricultural production such as direct use of energy in farm machinery, water management, irrigation, cultivation and harvesting. Agriculture accounts for only a relatively small proportion of total final energy demand in both industrialized and developing countries. As a result, governments and concerned individuals are working together at a global level to make the use of renewable resources a priority and to lessen the irresponsible use of natural supplies through increased conservation Kukreja (2017). The government of Zimbabwe is engaging youths to come up with innovations, which can be used for both industry and commerce while Independent Power Producers (IPPs) are being engaged to increase their supply so as to add more power into the grid.

The idea of a solar powered solar refrigeration system is not new because a solar driven refrigerator was firstly recorded in Paris in 1852 by Albel Pifre; (Vire, 1979), and a solar boiler was used to supply heat to a crude absorption machine, producing little amount of ice.

1.2 Problem statement

About 15% of the total electricity produced in the world is consumed for the refrigeration and air-conditioning, and about 45% of the total energy consumed by the commercial buildings and residences is used for air-conditioning and the demand is increasing continuously with time (Fan et al., 2007). This is resulting in energy shortages in most countries, including Zimbabwe. Due to the energy shortages, it is important to implement the use of renewable resources in industry and commerce sectors. Although some work has been done on saving the available electric power and improving productivity in the agriculture sector of Zimbabwe by developing solar based boreholes, a lot is still required to be done because challenges are still being experienced in preserving the freshness of fruits, vegetables and flowers in the horticulture sub-sector due to shortage of electricity power in the country. As a result, this necessitates the development of a solar refrigeration system; which can be used to preserve-horticulture products until their transportation.

1.3 Objectives

The objective of this thesis is to establish a fundamental basis for further research and development within the field of solar cooling that can adopt Zimbabwe's climate conditions.

The study aims to design a refrigerator, which runs efficiently on electricity provided by the sun and may include photovoltaics (PVs) or solar thermal energy. The researcher also aims to understand more on refrigeration systems being used on a larger scale, that is, for commercial horticulture farmers. The following are objectives of the project:

i. To study the solar refrigeration theorem.
ii. To analyse the annual weather reports of Zimbabwe.
iii. To size PV modules.
iv. To develop and design a refrigerator or cold room that is used to keep horticulture products fresh for a longer period.
v. To test and evaluate the final system

1.4 Research questions

i. How is the solar refrigeration theorem going to be useful in the development of the system?
ii. Is the system going to adopt the climate conditions of Zimbabwe?
iii. Which type of solar concentrating technologies is to be used, how many PV modules are required, and how much electrical energy is to be supplied to the refrigeration?
iv. How is the system going to be implemented on a large-scale for commercial horticulture farmers in Zimbabwe, and; is the design economically feasible in Zimbabwe?
v. How is the design going to be helpful in reducing electric power being withdrawn from the grid and also how is the system going to increase productivity in agriculture?

1.5 Significance of the study

Firstly, the research has significance to those horticulture farmers who are finding it difficult to pay or to cut down electricity bills. Also, it is important to individuals who are in the sectors facing electricity supply shortages. Furthermore, due to the energy crisis in Zimbabwe, it is important to reduce the amount of electricity withdrawn from the grid by using any available options. The research has significance because from the objective of the Conference of the Parties 26 (COP26), which clearly states that countries need to harness renewable energy resources to improve the available energy, and also to reduce pollution in the atmosphere, solar energy seems have gathered momentum during the last few decades. Hence, the research aims to use the available option of solar energy to improve economic sustainability, since Zimbabwe depends on the agriculture sector. Lastly, apart from that, the study may also be cited as the point of reference for those who wish to take similar studies in the future, and also for those who wish to make improvements of the system being proposed.

1.6 Delimitations of the study

- The study only focusses on the designing of a solar-powered refrigeration system that is intended to be used by large scale-horticulture farmers to preserve their products.
- The study only focusses on implementing the solar-powered refrigeration system in Mashonaland Central in Zimbabwe.

1.7 Limitations of the study

- The study required significant financial resources, and the researcher had no such funds readily available. Hence, in some cases, the researcher had to borrow either from family, friends or banks, to complete the study within the time frame given by the University.
- Access to certain online publication required payments; hence, the researcher had to rely mostly on free online articles.

1.8 Assumptions of the study

Refrigeration system is very sensitive to high temperatures, because high temperatures affect the mass flow of the refrigerant required to satisfy the cooling needs. Therefore, it is assumed that the system efficiency was not compromised by the temperature in Zimbabwe.

1.9 Definition of key terms

i. Solar system

A solar system consists of all those object that are governed by the sun's gravitational field. The solar system extends out to a distance of about two light-years, the closest star, Proximal Centauri, itself lying at a distance of slightly more than four light years.

ii. Refrigeration system

Refrigeration is a process of providing and maintaining temperature below the atmosphere. The medium used for refrigeration process is called a refrigerant. In normal refrigeration systems, the heat rejected in a condenser gets wasted. This rejected heat can be used for domestic purposes, like heating water, bathing, washing clothes and pots. The main advantage of simultaneous heating and cooling is that it can be carried out from one vapour compression refrigeration system. The effectiveness of refrigeration systems relies on the refrigerant (Alahmer & Ajib, 2018).

iii. Horticulture

Horticulture is a production system based on vegetables and /or fruit production, both in fields, market gardens or orchards. Horticulture is the art and science of growing flowers, fruits, vegetables, trees, and shrubs, resulting in the development of the minds and emotions of individuals, the enrichment and health of communities, and the integration of the garden in the breadth of modern civilization. By this definition, horticulture encompasses plants, including the multitude of products that is food, medicine and; oxygen, which are essential for human survival; and people, whose active and passive involvement with the garden brings benefits to them as individuals and to the communities and cultures they comprise.

iv. Ejector refrigeration cycle

Ejector refrigeration is a thermally driven technology that has been used for cooling applications for many years and it has a much lower coefficient of performance (COP).

v. Exergy analysis

Exergy analysis is a thermodynamic analysis technique based on the Second Law of Thermodynamics which provides an alternative and illuminating means of assessing and comparing processes and systems rationally and meaningfully. It is an important tool in controlling energy loss during thermal desalination.

vi. Dynamic analysis

Dynamic analysis is a model used to simulate behaviour of a system in each step of operating time with obtained results resembling the experimental results and can simulate system performance as well.

1.10 Summary

The chapter presented the background, statement of the problem, research objectives and research questions. The chapter also highlighted the significance of the study, delimitations, limitations, assumptions and definition of key terms.

CHAPTER 2: LITERATURE REVIEW

2.0 Introduction

The world's energy demand is growing fast because of population explosion and technological advancements, as a result it is important to go for reliable, cost-effective and everlasting renewable sources for energy demand arising in future. In this chapter, the researcher introduces the body of literature of solar energy and its application in solar-driven refrigeration systems and also in solar cooling. The conceptual framework is described clearly as the ideas, facts and principles behind the project. Furthermore, the researcher explores on the available theories, discussing and evaluating showing how they have aided to the development of this project. The justification is then given at the end but after revealing some empirical evidence of similar systems and precisely on how the proposed system will benefit the large-scale farmers and researchers in Zimbabwe

In order to have a firm grasp on solar refrigeration precepts, we should have an understanding of concepts, like the importance of solar systems, structure of a solar panel, solar heater, cooling system, ejector refrigeration cycle, exergy analysis, dynamic analysis, type of cooling systems that are in place and how they are designed, and also solar thermal technologies.

2.1 Principle behind solar refrigeration

The job of the refrigeration cycle is to remove unwanted heat from one place and discharge it into another. To accomplish this, the refrigerant is pumped through a closed refrigeration system. If the system was not closed, it would be using up the refrigerant by dissipating it into the surrounding media; because it is closed, the same refrigerant is used over and over again, as it passes through the cycle removing some heat and discharging it. The closed cycle serves other purposes as well; it keeps the refrigerant from becoming contaminated and controls its flow, for it is a liquid in some parts of the cycle and a gas or vapour in other phases (Layton, 2021). Berg Chilling Systems (BCS) (2021) explains that the metering device is a point where we will start the trip through the cycle. This may be a thermal expansion valve, a capillary tube, or any other device to control the flow of refrigerant into the evaporator, or cooling coil, as a low-pressure, low-temperature refrigerant. The expanding refrigerant evaporates (changes state) as it goes through the evaporator, where it removes the heat from the substance or space in which the evaporator is located.

Heat will travel from the warmer substance to the evaporator cooled by the evaporation of the refrigerant within the system, causing the refrigerant to "boil" and evaporate, changing it to a vapour. Now this low-pressure, low-temperature vapour is drawn to the compressor where it is compressed into a high-temperature, high-pressure vapour. The compressor discharges it to the condenser, so that it can give up the heat that it picked up in the evaporator. The refrigerant vapour is at a higher temperature than the air passing across the condenser; or water passing through the condenser (water-cooled type); therefore, that is transferred from the warmer refrigerant vapour to the cooler air or water. In this process, as heat is removed from the vapour, a change of state takes place and the vapour is condensed back into a liquid, at a high-pressure and high-temperature.

The liquid refrigerant travels now to the metering device where it passes through a small opening or orifice where a drop in pressure and temperature occurs, and then it enters into the evaporator or cooling coil. As the refrigerant makes its way into the large opening of the evaporator tubing or coil, it vaporizes, ready to start another cycle through the system.

2.2 Previous related studies

A year-round dynamic simulation of a Combined Cooling, Heating and Power generation (CCHP) system has been performed (DaqiqShirazi et al., 2019). The proposed system is composed of an ejector cooling system, an Organic Rankine Cycle (ORC), a solar collector field, heat exchangers and hot and cold storage tanks. It is considered that a portion of the system input energy is provided by a solar collector field and an auxiliary heater supplies the extra required energy. The dynamic simulation of the introduced CCHP system is performed. The developed model is used to evaluate a year-round performance of the system for a residential building located in Tehran. The obtained results indicated that the proposed CCHP system can satisfy the building energy demand. Furthermore, it is shown that the ejector cooling system can provide the required cooling load during the hot season. The obtained results indicated that increasing the hot storage tank size does not improve the system performance, but it can shift the system peak load.

Vas (2019) presented experimental investigations of a solar cooling method, based on a principle of absorption, using activated carbon and methanol pair. The adsorbent system uses a portable absorber, during refrigeration cycle. A refrigerator with a quantity of 42 litres, is focused to design for the preservation of perishable food items in remote areas can be designed by modifying the various parameters.

A PV solar refrigeration system is considered as one of the most vital areas in photovoltaic application (Salilih et al., 2020). This research's work was aimed to study the effect of operating pressures of evaporator and condenser to the performance of directly coupled variable speed solar refrigeration system. Performance parameters which were considered in the study are compressor speed, power consumption, refrigerant mass flow rate, and cooling capacity. The working pressure of the refrigeration system at evaporator and condenser were expressed with the saturation temperatures. In this study, a sensitivity analysis was performed with two cases. In the first case, the working saturation temperature of the condenser was fixed to 49 °C, while the working saturation temperature of the evaporator was varied from −13 to −34 °C. In the second case, the saturation temperature of the evaporator was fixed to −24 °C, while the saturation temperature of the condenser was varied from 38 to 60 °C. In the first case, it was found that all the considered performance parameters were sensitive to variation in saturation temperature of the evaporator. In the second case, compressor speed and power consumption showed negligible sensitivity to variation in saturation temperature of condenser but the other two performance parameters that is refrigerant mass flow rate and cooling capacity showed significant sensitivity to variation in saturation temperature of condenser.

The Solar-driven Ejector Refrigeration System (SERS) may be a solution for solar cooling (Pérez et al., 2022). Nevertheless, the SERS performance is constrained when low to medium temperature solar thermal collectors, commonly installed for Domestic Hot Water (DHW) production, are used in warm climates. Consequently, this paper reformulates the SERS application as a novel fresh air-pre-cooling system for air handling units. Therefore, greater evaporating temperatures that enable the SERS adoption in Nearly Zero Energy Buildings (NZEB) are explored. In doing so, the seasonal performance under severe operating conditions is analysed considering the two-phase flow ejector geometry, as well as refrigerants with low global warming potential. Main results demonstrate a maximum seasonal coefficient of performance (COP) of 0.37 by using R717. Moreover, an average cooling capacity of 28.3 kW could be produced per kW of electricity if an optimized multi-ejector solution with R600 is adopted.

According to (Khan et al., 2017), solar absorption refrigeration system requires a continuous operation in many of its applications for example food storage and space cooling which in turn requires an efficient thermal energy storage system utilizing material with high heat of fusion, for example phase change materials (PCMs). This review is a comprehensive evaluation of suitable PCM selection, methodologies of integration, enhancements and challenges for operating temperatures of each component in a single-effect solar absorption system affecting its performance. The purpose of this study was to observing the effects of PCM enhancement on the performance of the system, PCM enhancement options, energy, exergy and cost analysis are made for the future research direction

Khan et al. (2016) state that the major challenge in actualizing the use of solar energy to drive cooling systems such as absorption chillers is its intermittent nature, thereby not able to cover significantly the period of cooling demand in most situations. In order to achieve continuous cooling energy supply from solar driven absorption chillers, the study considered two alternative storage units in the form of chilled water and ice, integrated to the main chiller installed in Dhahran, Saudi Arabia. The system is designed to allow different operational modes in accordance with the cooling demands. The system is tested experimentally where the storage units are used alternatively and the results are presented. A mean chiller cop for cooling the space and chilling the water was found to be 0.8 whereas it was 1.3 for only making ice.

Maximum COP (0.8) was found at Tgen = 120 °C at an average condenser and evaporator temperatures of 34.5 and −2.2 °C, respectively.

Sebarchievici and Sarbu (2013), provide detailed review of different solar refrigeration and cooling methods. They present theoretical basis and practical applications of cooling systems within various working fluids assisted by solar energy and their recent advances. Thermally powered refrigeration technologies are classified into two categories that is sorption technology and thermo-mechanical technology. Solid and liquid desiccant cycles represent the open system. The liquid desiccant system has a higher thermal COP than the soli desiccant system. Absorption and absorption technologies represent the closed system. The absorption cooling typically needs lower heat source temperatures than absorption cooling. Based on the coefficient of performance, the absorption systems are preferred to absorption systems, the higher temperature issues can be easily handled with solar absorption systems. The ejector system represents the thermo-mechanical cooling, and has a higher thermal cop but require a higher heat source temperature than other systems. The study also refers to solar hybrid cooling systems with heterogeneous composite pairs, to a comparison of various solar cooling systems, and to some use suggestions of these systems

A statistical analysis of variance (ANOVA) approach was used to analyse and to optimize the solar absorption refrigeration unit for general applications Tashtoush (2012). It was found that the coefficient of performance of a solar adsorption refrigeration (SAR) system does not depend sharply on the evaporator temperature without any relation of the system conditions. Instead COP depends significantly on condenser temperature; type of couple used in the refrigeration system and on some factors that concern about the design such as surface areas. From the optimization model, the maximum value of COP was found to be under the low condenser temperature of below 27 °C and at the high generator temperature of above 80 °C.

Khalil (2012) conducted a research study on development and performance evaluation of a solar thermal collector that warms up air as a transferring medium of heat for drying of grains. The statistical analysis showed that an increase of 1 in mass flow rate significantly increases the performance of the solar collector. Also, there was decrease in performance by the change months of year. The efficiency was 10% higher in November the previous year as compared to January 2012. It was concluded that for drying of grains, the solar thermal collector must be operated at high mass flow rates of air from 9.00 am to 4.00 pm to get maximum performance from the solar thermal collector used for grain drying.

MacPhee et al. (2012) investigated the performance of four main types of ice storage techniques for space cooling purposes, namely ice slurry systems, ice-on-coil systems and encapsulated ice systems is conducted. The ice making techniques are compared on the basis of energy and exergy performance criteria including charging, discharging and storage efficiencies, which make up the ice storage and retrieval process. Losses due to heat leakage and irreversibilities from entropy generation are included. A vapour-compression refrigeration cycle with a working fluid provides, the cooling load, while the analysis is performed in both full storage and partial storage process, with comparisons between these two. In the case of full storage, the energy efficiencies associated with the charging and discharging processes are well over 98% in all cases, while the exergy efficiencies ranged from 46 to 76% for the charging for charging cycle and 18 to 24% for the discharging cycle. For the partial storage systems, all energy and exergy efficiencies were slightly less than full storage, due to the increasing effect wall heat leakage has on the decreased storage volume and load

A variety of solar cooling schemes have been economically and environmentally analysed to reveal some key details regarding system choice (Otanicar et al., 2012). For solar electric cooling system, the cost is highly dependent on the system cop when PV prices remain at the current level but when prices are lowered the impact of cop on cost diminishes. For solar thermal cooling, the cost of solar collection is much lower as a percentage of the overall cost, but the cost of the refrigeration system represents a larger percentage of the total cost. Additionally, the paper reveals that the costs for solar thermal cooling are not projected to decrease as much as PV cooling over the next 20 years due to the relatively stable cost of collection and storage. Solar electric cooling, even with the associated impact of refrigerants with global warming impact, have a lower projected emission value of carbon dioxide per kWh of cooling than any of the thermal technologies due to the much larger cop values associated with solar electric cooling. Another additional favourable aspect to solar electric cooling systems is the collector area foot print.

Aktacir (2011) reported a PV powered multi-purpose refrigerator system, which was erected to investigate experimentally its daily and seasonal operating performances based on semi-arid climatic conditions of Sanliurfa province in Turkey. It is one of the sunniest rural regions in the world and hence the need for refrigeration is critical. The overall results revealed that PV-refrigerator system can be reliably used in places where the local grid was unreliable and the refrigeration need is critical. On observation, the following results were observed – Low temperature of 10.6 degree Celsius was reached in the refrigerator, the highest energy amount produced by PV panels was recorded and the amount of energy consumed by the refrigerator was determined, the amount of energy stored in the battery bank was 78.2 Wh/day, while the amount of electric energy produced by PV panels was 425.9 Wh/day

2.3 Gap analysis

The issues of moving to green energy, reduce pollution and improve electrical power supply has made wide strides around the world. The reviewed literatures; however, left some gaps pertaining the implementation of the refrigeration system to commercial horticulture farmers. Firstly, most of the reviewed literature mainly focused on the refrigeration system at small-scale and air conditioning. Secondly, most of the reviewed were case study of buildings, as a result less exposure of the system to external weather conditions

2.4 Chapter summary

This chapter presents literature review of the study. Literature review is important as it provides the information related to the theories which are linked to the study. This chapter also involves principle behind the operation of a solar refrigerator which provides what other scholars did in the same field. Furthermore, literature review entails the research gap, which provides the justification of why the study has to be conducted.

CHAPTER 3: RESEARCH METHODOLOGY

3.0 Introduction

The main focus of this section is on identifying the procedures of the research, how data for the research project was collected, as well as describing the quantitative and qualitative techniques employed. The main objective was to develop a solar refrigeration system than is implemented in Zimbabwe to cut off the power deficiency being faced by farmers. This chapter mainly focuses on methodology, data collection approaches, research design, functional and non-functional requirements which govern the outcome of the research process.

3.1 Functional requirements of the system

- The system should be able to preserve horticulture perishables.
- The system should be able to maintain low temperature throughout the year.
- The system should be able to work efficiently in high temperature regions.

3.1.1 Development model

The researcher used the Prototyping Development model as this will allow the system to be tested whilst working with some limited functions. Prototyping is used to allow the user evaluate developer proposals and try them out before implementation.

3.1.2 System implementation

The system was implemented by using TRNSYS because the system configurations of the solar-assisted desiccant-based air-conditioning system and refrigeration system are modelled and simulated in TRNSYS for a given climatic conditions.

3.2 Research design

The research was done through some observations and some background of solar-driven refrigeration system. The following part fully explains how the system is going to be simulated, modelled and tested when the system is complete.

3.2.1 Observations

Various observations were made in developing and simulation of the system.

3.2.2 Existing refrigeration system

They many technologies of solar driven refrigeration system, and this include the following:

i. Absorption refrigeration

Absorption refrigeration is the least intuitive of the solar refrigeration alternatives. Unlike the PV and solar mechanical refrigeration options, the absorption refrigeration system is considered a heat driven system that requires minimal mechanical power for the compression process. It replaces the energy-intensive compression in a vapour compression system with a heat activated thermal compression system. On this system, the refrigeration unit can be either a continuous or an intermittent absorption system. The continuous absorption refrigeration system cannot serve the purpose if the pumps require power (Buel, 2018).

ii. Photovoltaic operated refrigeration cycle

PV involve the direct conversion of solar radiation to dc electricity using semiconducting materials. In concept, the operation of PV-powered solar refrigeration cycle is simple. Solar PV panels produce dc electrical power that can be used to operate a dc motor, which is coupled to the compressor of a vapour compression refrigeration system. The major considerations in designing a PV-refrigeration cycle involves appropriately matching the electrical characteristics of the motor driving the compressor with the available current and voltage being produced by the PV array. The rate of electrical power capable of being generated by a PV system is typically provided by manufactures of PV modules of standard conditions.

iii. Solar mechanical refrigeration

Solar mechanical refrigeration uses a conventional vapour compression system driven by mechanical power that is produced with a solar-driven heat power cycle. The heat power cycle usually considered for this application is a Rankine cycle in which a fluid is vaporized at an elevated pressure by heat exchange with a fluid heated by solar collectors. A storage tank can be included to provide some high temperature thermal storage. The vapour flows through a turbine or piston expander to produce mechanical power, as shown in Figure 3. The fluid exiting the expander is condensed and pumped back to the boiler pressure where it is again vaporized. The efficiency of the Rankine cycle increases with increasing temperature of the vaporized fluid entering the expander. The efficiency of a solar collector, however, decreases with increasing temperature of the delivered energy

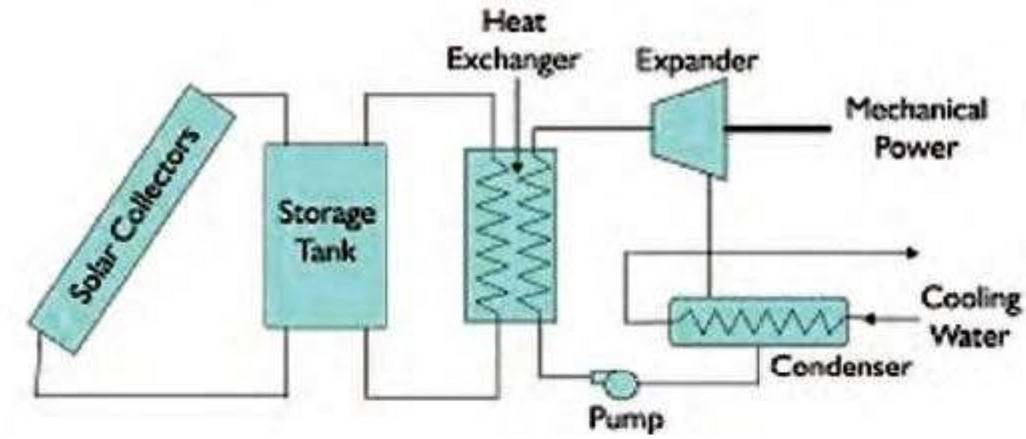


Fig. 3.1. Solar mechanical refrigeration cycle.

3.2.3 Verification

For verification is to be done so as to ensure that the project provides the required functionality and achieve the stated objectives. Verification is done when the development process starts. Verification's main goal is to meet the requirements which are specified.

3.3 Design method

3.3.1 System structural design

The system architecture consists mainly of three parts.

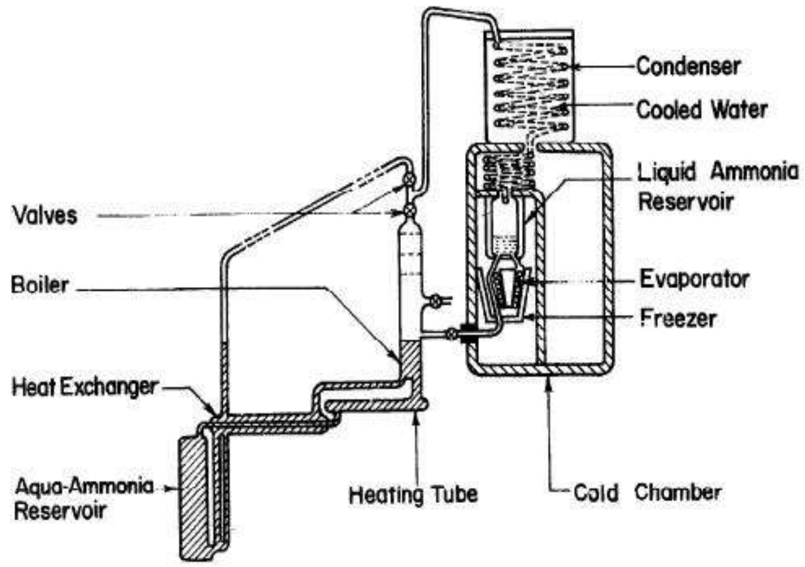


Fig. 3.2. Intermittent absorption refrigerator built by Tronde and Foex 1964 (Dong-Seon, 2007).

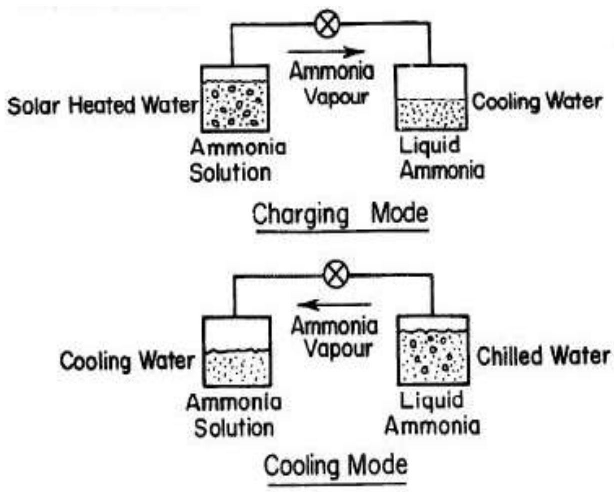


Fig. 3.3. System architecture of a solar absorption system.

3.3.2 The trnsys model of a solar driven refrigeration system

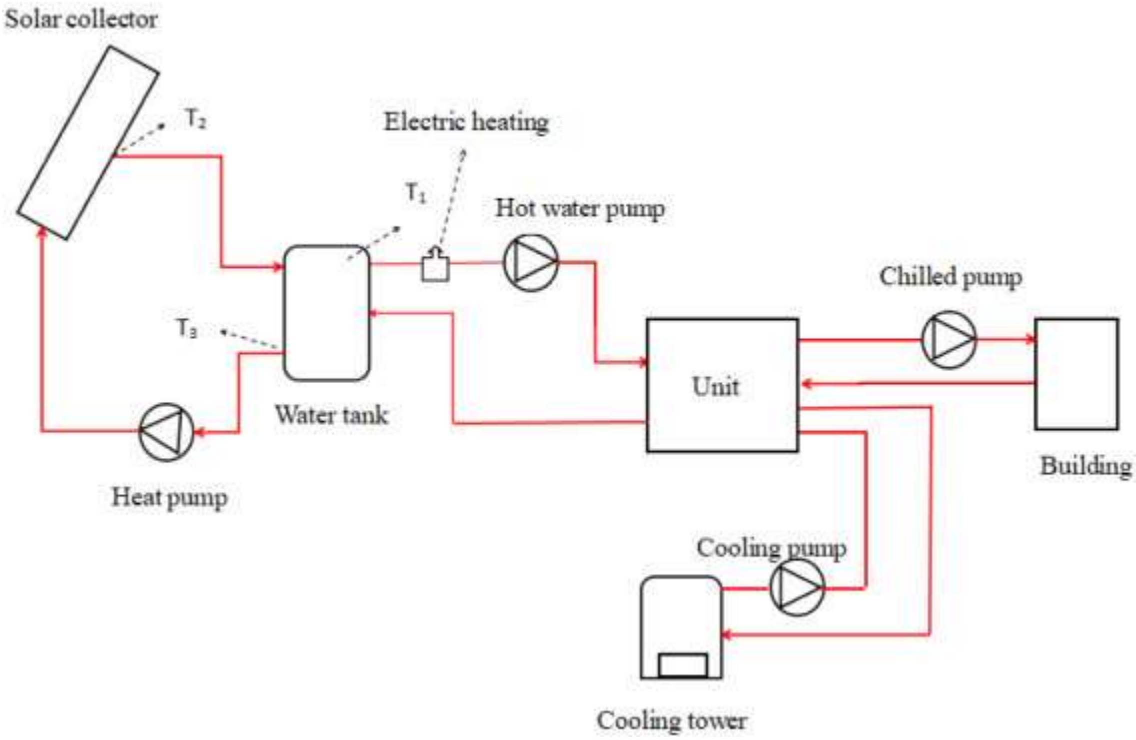


Fig. 3.4. TRNSYs model of a solar driven refrigeration system diagram.

3.4 Components of a solar-driven-refrigeration system

3.4.1 Solar panel

Solar photovoltaics collect energy from the Sun in the form of sunlight and convert it into electricity that can be used to power the refrigeration system.

3.4.2 Absorber

The absorber enables the refrigerant to flow by absorbing from the absorber to the generator. The absorber loop serves to absorb the refrigerant, then increases its pressure. The resulting solution continues in the cycle rejecting heat from the condenser at high pressure, then expanding and absorbing the heat in the evaporator at lower pressure.

3.4.3 Generator

It is used to generate the vapour refrigerant in generator outlet. The generator is used to create the same task as of the compressor in the conventional compression refrigeration cycle. It is located where the heat is available from the exhaust gases.

3.4.4 Condenser

The purpose of the condenser is to receive the high-pressure gas from the compressor and convert this gas to a liquid. It does it by heat transfer, or the principle that heat will always move from a warmer to a cooler substance.

3.4.5 Expansion valve

Expansion valves are devices used to control the refrigerant flow in a refrigeration system. They help to facilitate the change of higher pressure of liquid refrigerant in the condensing unit to lower pressure gas refrigerant in the evaporator.

3.4.6 Evaporator

The main job of the evaporator coil is to cool the refrigerant so that it can absorb the heat. As the fan blows air over the coil, the refrigerant becomes cold and turns into a vaporous state.

3.4.7 Fan

They are two fans on refrigeration system. One is under the refrigerator to cool the compressor and force air through the exterior coils. The second is inside and moves air around the coils inside the refrigerator. This second fan helps provide more even cooling, and also aids in the defrost process.

3.4.8 Heat pump cycle

Heat pump cycle, is also called the refrigeration cycle, is a means of routing heat away from the area you want to cool. This is achieved by manipulating the pressure of the working refrigerant through a cycle of compression and expansion.

3.5 Experiment and test sets

In order to design a solar driven refrigeration system that is to be implemented in Zimbabwe, there is need for experiments to be carried out, for the purpose of observing if the refrigeration system runs perfectly with the climatic conditions. Fig. 3.5 shows the experimental unit.

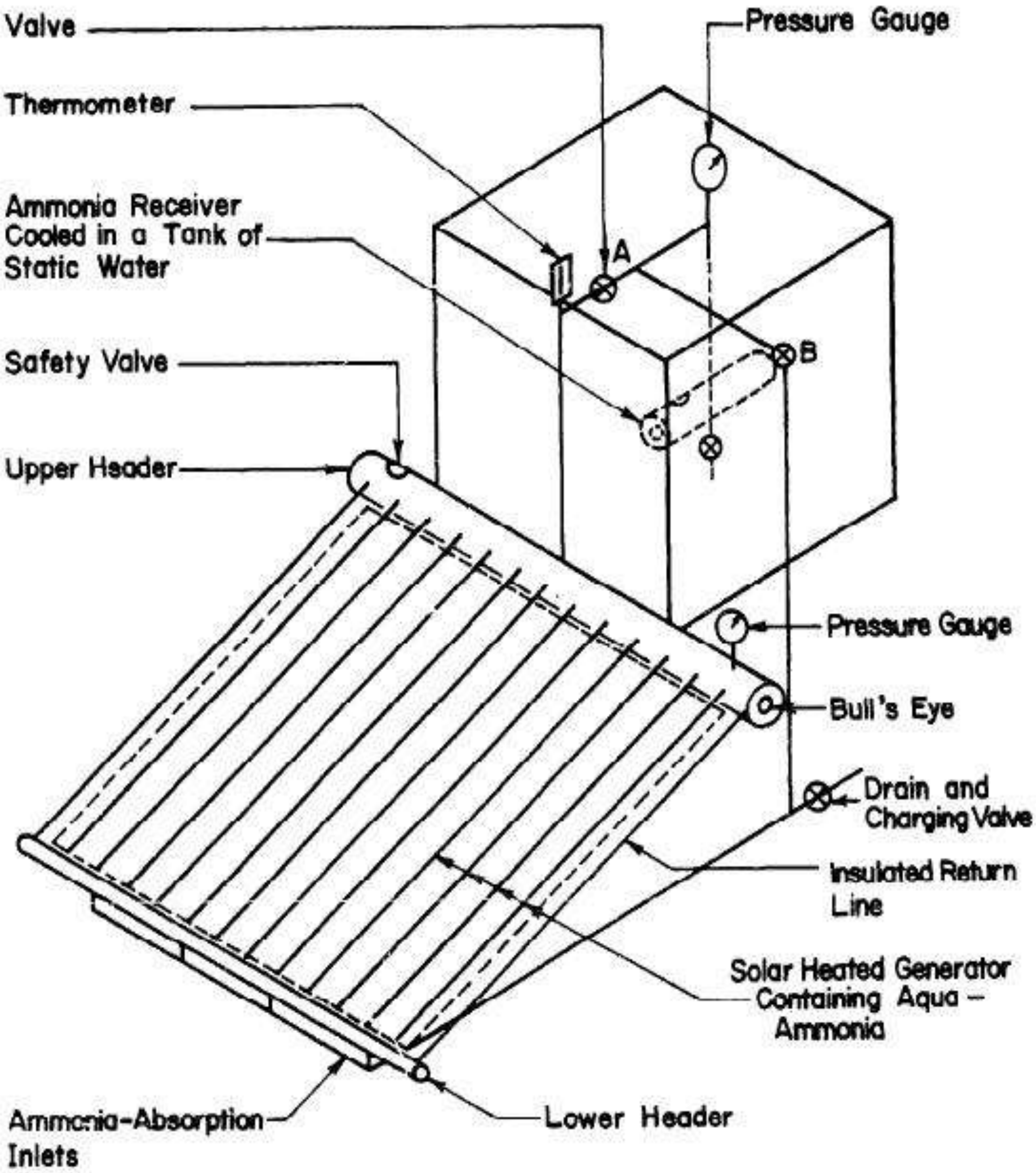


Fig. 3.5. Experimental unit.

3.5.1 Operation of the system

During the regeneration, one valve opens and another valve closes, and the solution in the generator being heated by the collector boils, giving vapour at a high pressure. The weak solution returns from the top header to the bottom header by the insulated return pipes. The vapour in the top header is mainly ammonia because water has a much lower volatility than ammonia. The ammonia vapour passes into the condenser which is immersed in a tank of cold water to keep it cool. The pressure is uniform throughout the system. When heating stops one valve is closed and the vapour pressure in the generator drops. The concentration in the generator is now less than it was before regeneration. Before refrigeration is started the tank of cooling water is removed and another valve is opened. The condenser now functions as the evaporator. Ammonia vaporizes due to the pressure difference between the generator and evaporator.

3.5.2 Experiment aimed to find the relationship between plate temperature and solution temperature

1. The collector-generator was first charged with water and temperature measurements were made using thermometer to find the relation between the plate temperature and solution temperature.
2. Note the temperature T_o of water
3. Set the stop clock to zero and note down its least count.
4. A stop clock is set to measure the time for temperature to fall down.
5. Stop the clock when the fall of temperature becomes very slow.
6. Make observation and record.

3.5.2.1 Result

The temperature is seen to fall quickly in the beginning and then the difference in temperature slowly decreases. This is in agreement with Newton's law of cooling which state that the rate of cooling of a body is directly proportional to the temperature difference between the body and the surrounding, provided the temperature difference is small.

3.5.2.2 Efficiency measures

An overall system COP can be defined as the ratio of refrigeration capacity to input solar energy. It can also be defined as the ration of the cooling obtainable to the amount of solar energy absorbed by the collector plate. However, this definition of efficiency may not be the most relevant metric for a solar refrigeration system because the fuel that the system uses during operation is solar energy and it is free.

3.6 Calculation of required solar PV modules

In Zimbabwe, a huge irrigation program spearheaded by the government and development partners for 189 communal farmers farming citrus fruit has improved many rural lives. At the irrigation-driven citrus project, the 189 communal farmers are currently producing 700 to 1000 tonnes of oranges on average per farmer and per season to feed the Schweppes Holdings-run Beit-bridge Juice Plant (Muleya, 2022). Each farmer will need to establish a 5 MT solar-powered cold room in order to keep their livestock fresh for a brief length of time. The number of panels required is 60 as pshown in Appendix 2a.

Project summary

Geographical Site	Situation		Project settings	
Bindura	Latitude	-17.30 °S	Albedo	0.20
Zimbabwe	Longitude	31.33 °E		
	Altitude	1120 m		
	Time zone	UTC+2		

Meteo data
Bindura
Meteonorm 8.0 (1991-2005), Sat=94% - Synthetic

System summary

Stand alone system | **Stand alone system**

PV Field Orientation
Fixed plane
Tilt/Azimuth 30 / -17 °

User's needs
Daily household consumers
Constant over the year
Average 260 kWh/Day

System information

PV Array		Battery pack	
Nb. of modules	100 units	Technology	Lithium-ion, NMC
Pnom total	70.0 kWp	Nb. of units	4 units
		Voltage	1439 V
		Capacity	593 Ah

Results summary

Available Energy	137908 kWh/year	Specific production	1970 kWh/kWp/year	Perf. Ratio PR	58.17 %
Used Energy	94945 kWh/year			Solar Fraction SF	100.00 %

Table of contents

Fig. 3.6. PVsyst simulation of the system solar array.

3.7 Conclusion

In this chapter, an analysis was done which resulted in a research methodology, helping in modelling solar-driven refrigeration system. Following the use of TRNSYS software, the simulation of the system was implemented in the project development.

CHAPTER 4: DATA PRESENTATION, ANALYSIS AND INTERPRETATION

4.0 Introduction

System analysis is a method of problem-solving that involves disassembling a system into its component parts in order to understand how each part functions and interacts with the others to achieve the system's objectives (Abdullah, 2020). The researcher's goal in this chapter is to analyse in detail the system response, strength and weaknesses among other areas, both in the current and proposed solar driven refrigeration system.

4.1 Implementation

The system is being implemented by using flat-plate solar collectors or solar ponds, and refrigerant-absorbent pairs which provides cooling or refrigeration at subzero (°C) temperatures. It is demonstrated that the use of R404A and suitable organic solvent systems is desirable in absorption refrigeration installations.

4.1.1 Testing techniques

The researcher used the following testing strategies for the system. The researcher was primarily concerned with developing the refrigeration system, calculating the capacity of each component to be used, and calculating the system's coefficient of performance (COP).

4.1.2 Objectives

The researcher firstly sized the system and its components before determining if it works properly and according to specifications.

4.2 Specification of cold room

Except for a few commodities such as apples, oranges, potatoes, cabbage, and so on, the storage life of fruits and vegetables even at low temperatures ranges from 2 to 4 weeks. In the case of a cold room, long-term storage is not anticipated, and the duration of storage is likely to be 1 to 4 weeks.

4.2.1 The cooling unit

The cooling unit employed R 404A refrigerant. Inside the chamber, a temperature range of 2 to 6°C was maintained. The temperature was 28°C outside. The total refrigerant capacity was be 10.8 kW for a cool chamber with a capacity of 5 metric tonnes (MT).

4.2.2 Chamber size

For a 5 MT capacity cool chamber, the chamber dimensions were 10 × 8 × 4. M.S. channels and angles were used to construct the storage.

4.2.3 Insulation

For insulating the cold room walls and ceiling, a 60 mm thick PUF panel was provided.

Floor insulation was provided in the form of an 80 mm EPS slab, PCC, and KOTA stone. Chicken wire is commonly used to strengthen insulation.

4.2.4 Power supply

Electric load was 10.82 kW for 5 MT. Power supply was 230 Volt AC ± 10% 50/60Hz.

4.2.5 Electrical work

The main power distribution switch board, feeder switches for cooling units, capacitors, power distribution cables, electric lighting, and equipment earthing are all part of the electrical work.

4.2.6 Standby generator

A standby generator was installed to meet power requirements during the night or when there was a fault, as well as on cloudy days when the solar PV modules trap less sunlight. The generator had out starting device to start it if the power goes out.

4.3 Calculation of the refrigerating power

Table 4.1 shows the required specification of the cold room.

Table 4.1. The cold room's required specification.

Sl. No.	Particulars	Specifications
1	Capacity	5MT
2	Outside temperature	43 °C
3	Cold room temperature	4 °C (± 2 °C)
4	Outside moisture	50 %
5	Type	Pre-fabricated room with floor
6	Internal room dimension	10m x 8m x 4m
7	Insulation	Poly-urethane foam
8	Insulating surface	60mm thick
9	Turn over	Long storage
10	Man powers	2 nos.
11	Light	160 watt
12	Motor power	225 watt
13	Motor running period	24hrs/ day
14	Product	Fruits
15	Process	Fresh product storage
16	Product entering temperature	28 °C
17	Product leaving temperature	4 °C (± 2 °C)
18	Daily turnover	33 %
19	Process period	24 hrs

20	Density	145 kg/cum
21	Running compressor	18h/day

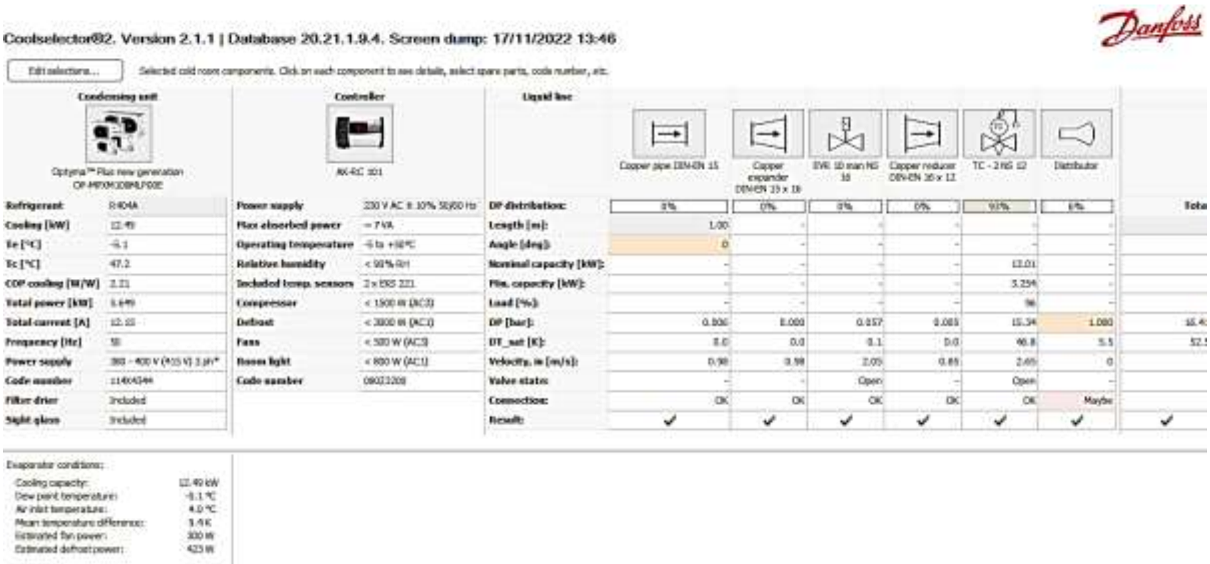


Fig. 4.1. Specifications of the refrigerator.

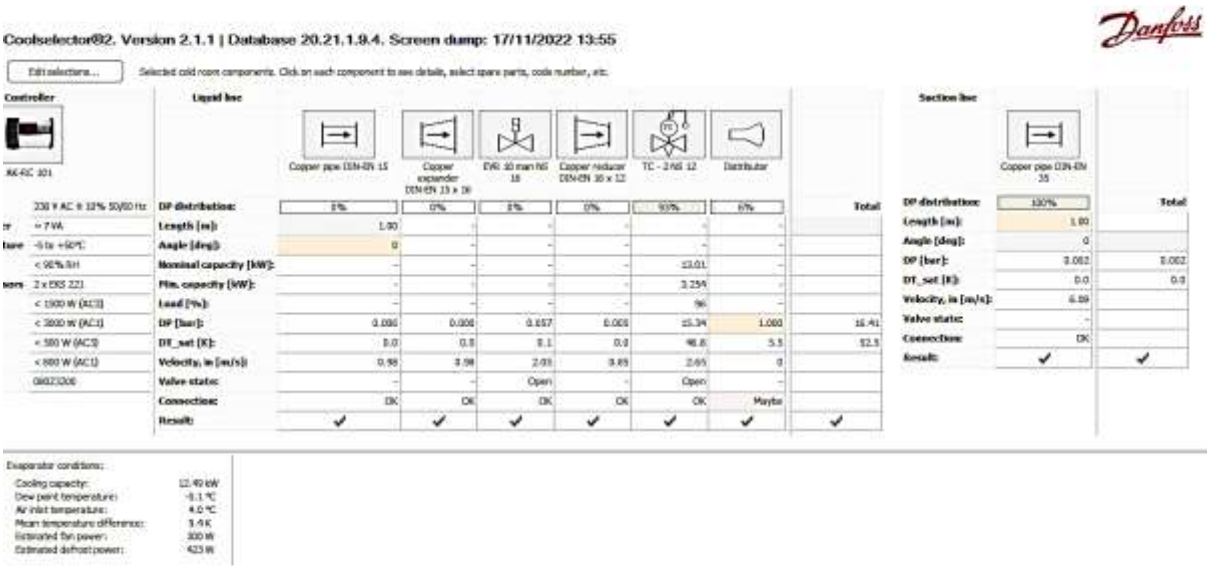
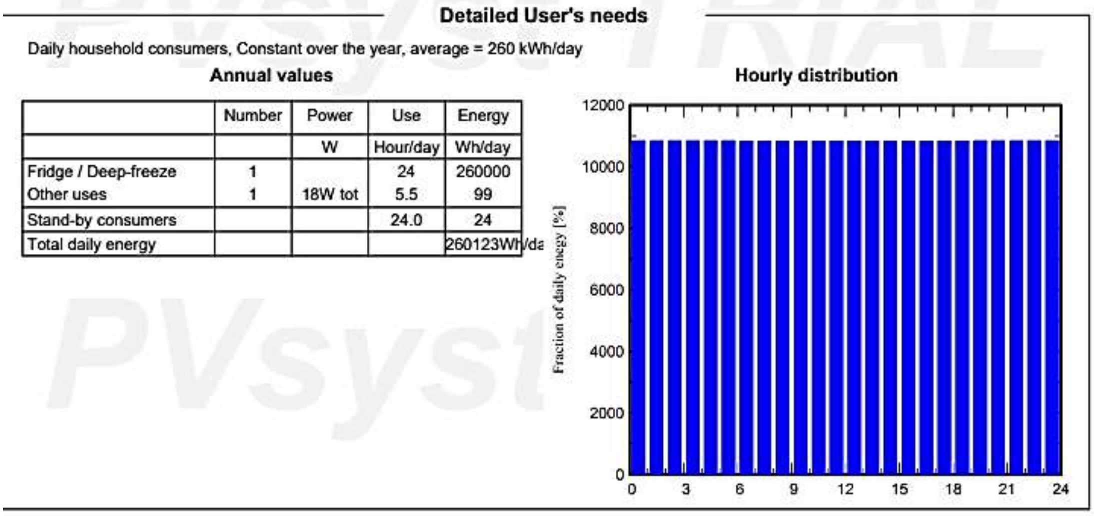


Fig. 4.2. Specifications of the refrigerator.

Fig 4.1 and 4.2 depict the results of the cold room simulation using the specifications listed in Table 4.1.

4.4 Solar system

Because the cold room has a load capacity of 10.82 kW and operates 24 hours a day, a solar system should be able to supply enough electricity to power the system.

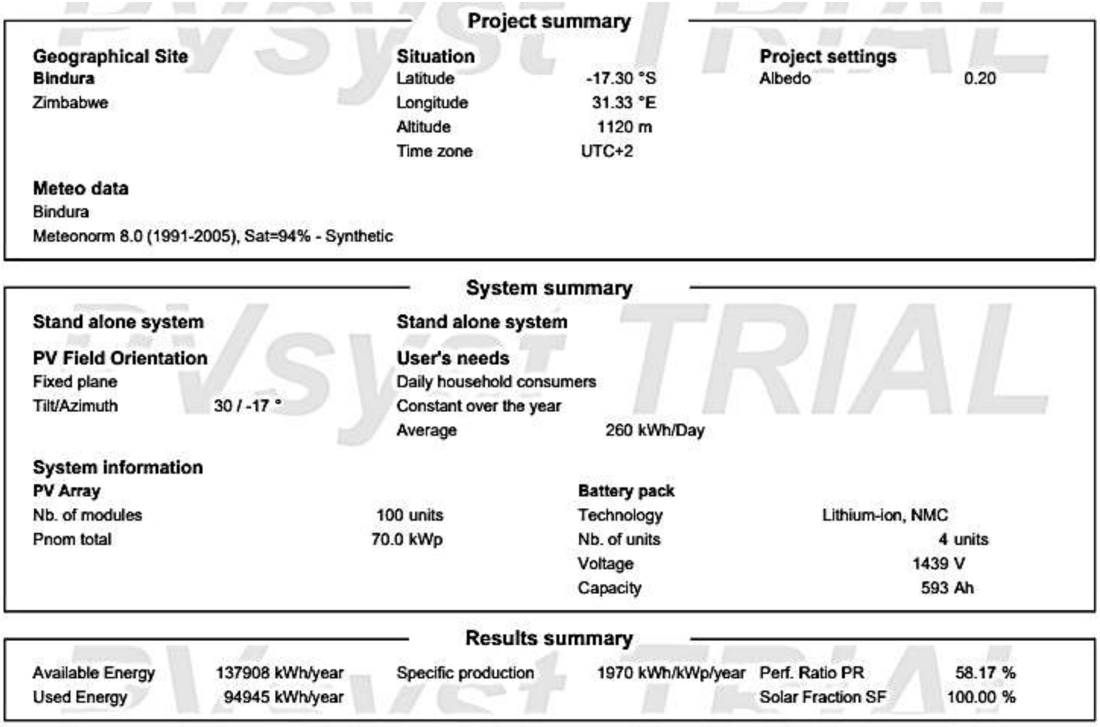


	Number	Power	Use	Energy
		W	Hour/day	Wh/day
Fridge / Deep-freeze	1		24	260000
Other uses	1	18W tot	5.5	99
Stand-by consumers			24.0	24
Total daily energy				260123Wh/da

Fig. 4.3. System power requirements in detail.

4.4.1 System feasibility test

Before a project can begin, a feasibility test must be conducted. A feasibility test is a thorough assessment performed prior to beginning any market research project to determine how feasible the project is. When done correctly, it will provide the foundation for a successful qualitative market research project.



Project summary

Geographical Site		Situation		Project settings	
Bindura		Latitude	-17.30 °S	Albedo	0.20
Zimbabwe		Longitude	31.33 °E		
		Altitude	1120 m		
		Time zone	UTC+2		

Meteo data
Bindura
Meteonorm 8.0 (1991-2005), Sat=94% - Synthetic

System summary

Stand alone system		**Stand alone system**	
PV Field Orientation		**User's needs**	
Fixed plane		Daily household consumers	
Tilt/Azimuth	30 / -17 °	Constant over the year	
		Average	260 kWh/Day

System information

PV Array		Battery pack	
Nb. of modules	100 units	Technology	Lithium-ion, NMC
Pnom total	70.0 kWp	Nb. of units	4 units
		Voltage	1439 V
		Capacity	593 Ah

Results summary

Available Energy	137908 kWh/year	Specific production	1970 kWh/kWp/year	Perf. Ratio PR	58.17 %
Used Energy	94945 kWh/year			Solar Fraction SF	100.00 %

Fig. 4.4. Solar system parameters.

Following an examination of all aspects of a proposed project, including technical, economic, financial, legal, and environmental considerations, it was determined that the project is feasible, as illustrated in Fig. 4.4.

4.4.2 Testing the climate conditions against system performance

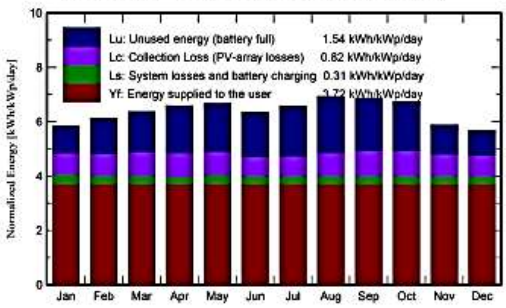
Zimbabwe receives an average of 20 mega joules per square meter, which could generate 10,000 gigawatt of electrical energy per year, and it receives far more direct solar irradiation than other countries in our region. Because of the high average solar irradiation, solar-driven refrigeration is expected to perform well almost all year, as illustrated below.

Main results

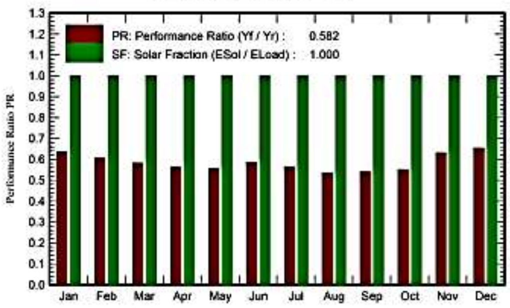
System Production

Available Energy	137908 kWh/year	Specific production	1970 kWh/kWp/year
Used Energy	94945 kWh/year	Performance Ratio PR	58.17 %
Excess (unused)	39371 kWh/year	Solar Fraction SF	100.00 %
Loss of Load		**Battery aging (State of Wear)**	
Time Fraction	0.0 %	Cycles SOW	98.4 %
Missing Energy	0 kWh/year	Static SOW	90.0 %

Normalized productions (per installed kWp)



Performance Ratio PR



Balances and main results

	GlobHor kWh/m²	GlobEff kWh/m²	E_Avail kWh	EUnused kWh	E_Miss kWh	E_User kWh	E_Load kWh	SolFrac ratio
January	215.5	175.2	10603	2130	0.000	8064	8064	1.000
February	188.1	167.2	10114	2544	0.000	7283	7283	1.000
March	194.4	193.9	11558	3194	0.000	8064	8064	1.000
April	176.0	194.6	11638	3630	0.000	7804	7804	1.000
May	164.1	203.7	12261	3818	0.000	8064	8064	1.000
June	143.3	187.7	11527	3435	0.000	7804	7804	1.000
July	155.2	201.1	12344	3976	0.000	8064	8064	1.000
August	179.6	211.8	12857	4487	0.000	8064	8064	1.000
September	193.4	202.3	12120	4036	0.000	7804	7804	1.000
October	219.8	204.1	12250	3888	0.000	8064	8064	1.000
November	205.4	171.5	10326	2251	0.000	7804	7804	1.000
December	216.4	170.2	10311	1983	0.000	8064	8064	1.000
Year	2251.2	2283.2	137908	39371	0.000	94945	94945	1.000

Legends

GlobHor	Global horizontal irradiation	E_User	Energy supplied to the user
GlobEff	Effective Global, corr. for IAM and shadings	E_Load	Energy need of the user (Load)
E_Avail	Available Solar Energy	SolFrac	Solar fraction (EUsed / ELoad)
EUnused	Unused energy (battery full)		
E_Miss	Missing energy		

Fig. 4.5. Solar system performance throughout the year.

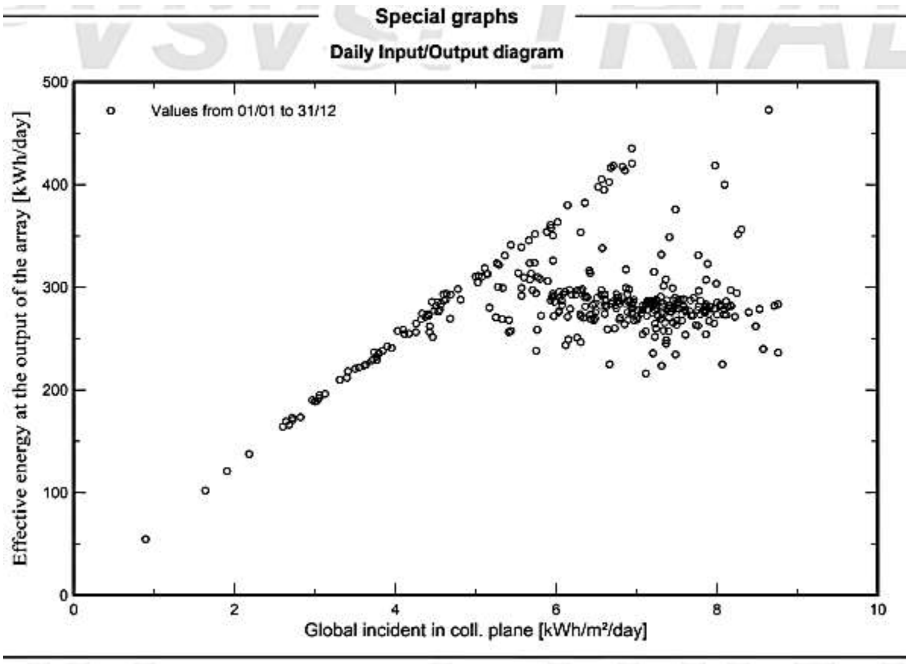


Fig. 4.6. Solar system daily input/output.

4.4.3 System costing

System costing refers to all costs associated with the system, including but not limited to capital costs, finance costs, operation and maintenance costs, and repair and replacement costs (Law Insider, 2022). The installation of a solar system necessitates a significant initial investment as shown in the bill of quantity BOQ in Appendix 1.

4.4.4 Energy savings

Total energy cost per year = Total energy generated per year × electricity tariffs

= 92 002.68 × 0.02

= US$ 1 840.05

As demonstrated by the above calculation, farmers can save a total of over US$ 1800 by using the solar-powered refrigeration system.

4.5 Testing against objectives:

- Did the researcher meet the research objectives?

- Did the researcher design a refrigerator or cold room that have the capacity to be implemented on a large scale by farmers?

Research objectives:

- To study the solar refrigeration theorem.
- To analyse the annual weather reports of Zimbabwe.
- To size PV modules.
- To develop and design a refrigerator or cold room that is used to keep horticulture products fresh for a longer period.
- To test and evaluate the final system

The following table illustrate the findings of the research against the objective of the research.

Objective	Outcome
To study the solar refrigeration theorem.	- To have a better refrigeration system, various theorems and some of the software used in the simulation and modelling of refrigeration systems were used.
To analyse the annual weather reports of Zimbabwe	-Analyses of Zimbabwe's annual weather reports, as some modelling softwares required the climate conditions for the simulation to take place. This was done while monitoring the overall system performance throughout the year.
To size PV modules	- The total number of PV modules was determined.
To develop and design a refrigerator or cold room that is used to keep horticulture products fresh for a longer period	- The system has been developed and is economically viable.

To evaluate the final system	-Yes

4.6 Conclusion

The researcher performed numerous calculations to ensure that the system met the research objectives and other functionalities required for the system to function.

CHAPTER 5: SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

5.0 Introduction

This chapter presents a summary of the study, along with a brief description of what each chapter covered. The chapter also presents the study's conclusion, including inferences about the research findings. Furthermore, the chapter presents the purpose of the research, the findings, and recommendations for future research.

5.1 Summary of the study

The first chapter of the study introduced the research with the study's background, in which concerns about energy shortages on supply and rising demand were discussed from a global to a regional to a local level. The discussion presented various authors', organizations', and energy companies' perspectives on the subject. Furthermore, the chapter presented the research objectives, which presented the goals that the research study aimed to achieve. The significance of the study presented the study's contributions to the body of knowledge. Furthermore, chapter 2 of the study presented a literature review in which various authors from journals, books, articles, and other published papers were evaluated based on their school of thought. The literature review discussed various aspects of solar-powered refrigeration systems and their effects on agricultural production and economic growth. The theoretical framework revealed a number of theoretical models on which the current system is based.

Furthermore, Chapter 3 of the study presented the research methodology, which examined various aspects of the study, including the research design and the calculations involving the number of panels. The research findings were presented in Chapter 4 of the study, which included the initial amount needed to implement the project, the annual energy cost savings, and simulation results of the refrigeration system and the solar system.

5.2 Research questions

i. How is the solar refrigeration theorem going to be useful in the development of the system?
ii. Is the system going to adopt the climate conditions of Zimbabwe?

iii. Which type of solar concentrating technologies is to be used, how many PV modules are required, and how much electrical energy is to be supplied to the refrigeration?
iv. How is the system going to be implemented on a large-scale for commercial horticulture farmers in Zimbabwe, and; is the design economically feasible in Zimbabwe?
v. How is the design going to be helpful in reducing electric power being withdrawn from the grid and also how is the system going to increase productivity in agriculture?

5.3 Discussion of results

The researcher was successful in producing results that met the research objectives. In the development of the system, research questions were also addressed. For example, the system is a stand-alone solar system that does not draw any electricity from the national grid.

5.4 Challenges

Because renewable technologies such as solar are still in their early stages of development, the researcher had to spend extra time understanding the available renewable technology in the agriculture sector and how they are reducing energy so that the system meets the research objectives.

5.6 Conclusion

Despite significant progress in the implementation of renewable energy technologies, solar-powered refrigeration systems were lacking in Zimbabwe. Several systems have been implemented in the agriculture sector to increase productivity and modernize the agricultural system. Despite some difficulties in the research, the researcher is able to develop a system that attempts to meet all of the research objectives as well as the needs of large-scale horticulture farmers.

5.7 Recommendations

This section outlines some recommendations for the system developed by the researcher as well as some issues that require further investigation. On the COP, the system developed will need to be improved. Furthermore, the system is supposed to be improved so that any faults that occur at any time are reported to the user's remote device.

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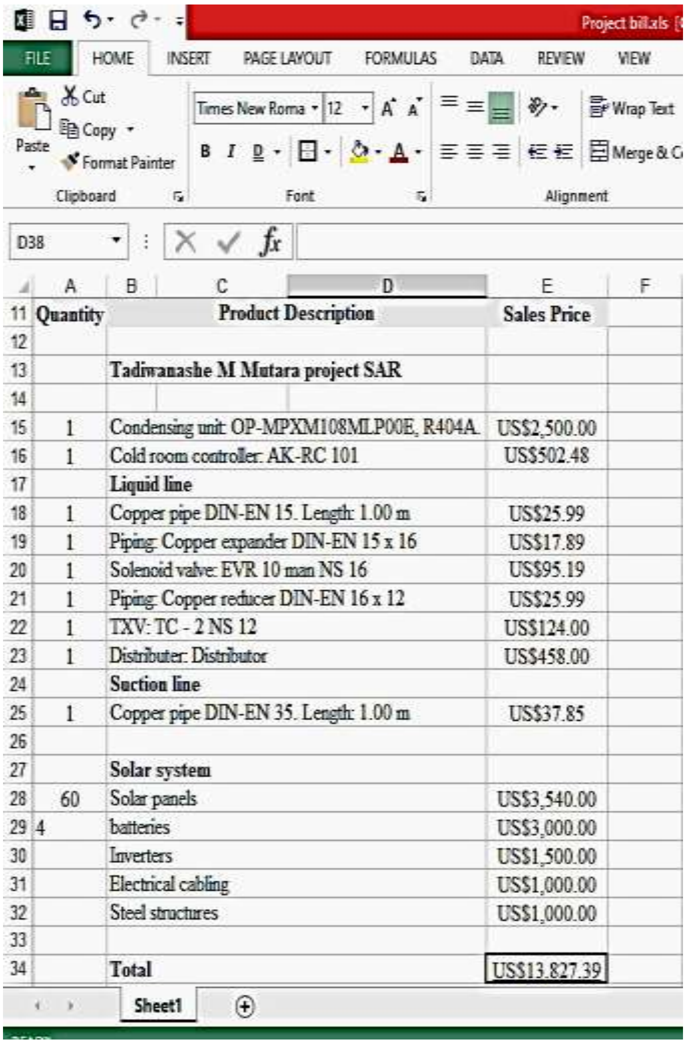
APPENDICES

Appendix 1

The BOQ of the solar refrigeration system is shown below.



Quantity	Product Description	Sales Price
	Tadiwanashe M Mutara project SAR	
1	Condensing unit: OP-MPXM108MLP00E, R404A	US$2,500.00
1	Cold room controller: AK-RC 101	US$502.48
	Liquid line	
1	Copper pipe DIN-EN 15. Length: 1.00 m	US$25.99
1	Piping: Copper expander DIN-EN 15 x 16	US$17.89
1	Solenoid valve: EVR 10 man NS 16	US$95.19
1	Piping: Copper reducer DIN-EN 16 x 12	US$25.99
1	TXV: TC - 2 NS 12	US$124.00
1	Distributer: Distributor	US$458.00
	Suction line	
1	Copper pipe DIN-EN 35. Length: 1.00 m	US$37.85
	Solar system	
60	Solar panels	US$3,540.00
4	batteries	US$3,000.00
	Inverters	US$1,500.00
	Electrical cabling	US$1,000.00
	Steel structures	US$1,000.00
	Total	US$13,827.39

Appendix 2

Objective 3: To size the PV modules

Solar power required = 10820 x 24 watt-hours ÷ 5.7 peak-sun-hours

= 45 557.9 watts

If 1kW Jinko solar panels were used, the number of solar panels for the average Zimbabwe solar systems would be 5.7kWh/m²/day

45 557.9 watts ÷ 1000 watts = 46 solar panels

Adjusted solar output = 45 557.9 x 1.4 = 63781.1 watts

Using 1kW solar panels, the actual number of solar panels needed would be:

63 781.1 watts ÷ 1000 watts = 60 solar panels

b) Energy savings

Total energy generated per day = Power * 24hr

= 10.82 * 24

= 259.68 kWh

Total energy generated per year = 259.68 * 365.25 days

= 94 848.12 kWh

But the system have inverters which have 95% efficiency hence:

Total energy generated = 94 900 x (0.97)

= 92 002.68 kWh / year

Total energy cost per year = Total energy generated per year x electricity tariffs

= 92 002.68 x 0.02

= US$ 1 840.05

c) Battery sizing

The system load is 10.82kW

System energy required = 10.82 x 24

= 259.7 kWh

For inverter efficiency = 10820 ÷ 0.8

= 13525 W

Battery capacity = 13525 ÷ 14.3

= 945.8 Ah

Including the days of autonomy

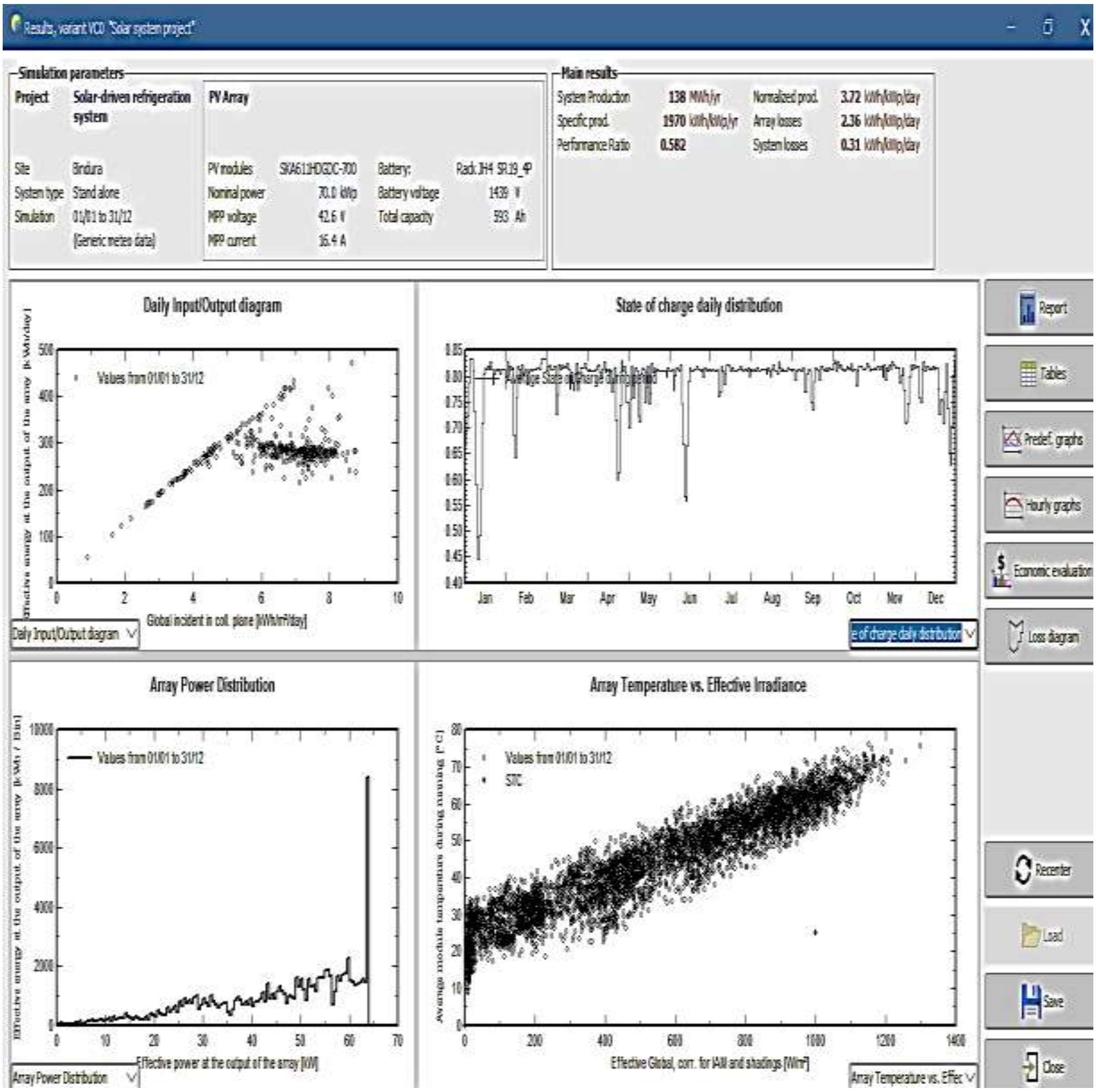
Required capacity = 945.8 x 3÷ 0.3

= 2372 Ah

Number of batteries = 2372 ÷ 593

= 4 (593 Ah) Li^{+} ion batteries

Appendix 3



Graphical results that shows the performance of the system if implemented in Zimbabwe.