DESIGN AND IMPLEMENTATION OF A STANDALONE SOLAR SYSTEM FOR DRUG PRESERVATION IN RURAL HEALTH CARE FACILITIES

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A PROJECT SUBMITTED TOTHE DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING IN PARTIAL FUFILLMENT OF THE REQUIREMENT FOR THE AWARD OF B.ENG DEGREE IN THE FACULTY OF ENGINEERING.

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CERTIFICATION

This is to certify that this project work was carried out by IYEYE EFETAKOKO GREATER, JOHN SAMUEL IYOBOR and MOMOH OTINAMHE JUSTIN of the Department of Electrical/Electronic Engineering, Faculty of Engineering, University of Benin, Benin City, Nigeria in partial fulfilment of the requirements for the award of Bachelor of Engineering (B.Eng.) degree in ELECTRICAL/ELECTRONIC Engineering

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Date

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Head of Department

Date

DEDICATION

This report is offered to God. We extend our heartfelt dedication to our parents, cherished ones and supporters, whose unwavering presence have been a beacon of support, especially during challenging times.

ACKNOWLEDGMENTS

Our deepest gratitude to the almighty who made our journey possible. We want to express our heartfelt thanks to Engr. Dr. T.A Aika, our project supervisor, whose committed efforts made putting together this report much easier, his constant support and guidance meant a lot to us throughout this project.

We also want to thank the the Department of Electrical/Electronic Engineering for creating an environment that supported the successful completion of this project, all to all the lecturers whose teachings have enriched our knowledge over the years. We also acknowledge the head of the department Engr. Dr. S. Omorogiuwa for his invaluable support and guidance.

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ABSTRACT

Rural primary healthcare centres in Nigeria face chronic electricity shortages that compromise the cold chain required for storing vaccines and temperature-sensitive medicines. Frequent power outages expose these medical products to temperatures outside the recommended +2°C to +8°C range, causing potency loss, treatment failures, and increased public-health risks. The project addresses this critical challenge by providing a reliable off-grid alternative capable of ensuring uninterrupted refrigeration in remote locations where grid power is unstable or unavailable.

The project adopts a systematic engineering approach involving load estimation, solar resource assessment, component sizing, and prototype assembly. A stand-alone solar photovoltaic system—comprising a 570 W panel, a 12 V/220 Ah deep-cycle battery, a 1 kVA pure sine-wave inverter, and a 30 A charge controller—was designed and constructed based on the energy requirements of a 60 W medical refrigerator. Field measurements were used to verify solar panel performance, battery charging behaviour, inverter compatibility, and the system's ability to maintain cold-chain temperatures under realistic operating conditions.

Testing showed that the solar PV system reliably powered the refrigerator and maintained continuous operation within the safe temperature range. The battery demonstrated an autonomy period of approximately 26 hours, while the solar array consistently delivered sufficient current for daily recharge. Results confirm that the system is technically viable, cost-effective, and capable of protecting temperature-sensitive drugs in rural healthcare settings. The findings validate solar-powered refrigeration as a sustainable solution to cold-chain failures in off-grid environments.

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CHAPTER ONE

INTRODUCTION

1.1 Background of the Project

Rural primary health centres in Nigeria continue to struggle with unreliable electricity supply, a challenge that directly threatens the cold chain required for storing vaccines and temperature-sensitive drugs. When medicines such as insulin, antivenoms, and immunization vaccines are exposed to temperatures outside the recommended +2°C to +8°C range, their potency rapidly declines, creating serious public health risks. As global energy systems shift toward sustainability and fossil fuels become less viable, solar energy stands out as a dependable, affordable, and environmentally responsible alternative.

This project proposes the design and assembly of a stand-alone solar power system specifically engineered to provide stable, off-grid energy for medical refrigeration. By leveraging solar technology, the project aims to ensure consistent cooling performance in remote or underserved regions, safeguarding drug quality and improving healthcare reliability.

1.2 Statement of the Problem

The frequent power outages experienced in rural Nigerian health facilities compromise essential healthcare services. The inability to maintain cold-chain temperatures leads to ineffective treatments, wastage of medical resources, and preventable health complications. Current alternatives, such as diesel generators, are expensive to operate, environmentally harmful, and often unavailable. There is a critical need for a sustainable and reliable energy source that can operate independently of the grid and provide uninterrupted power to vital cold-chain equipment.

1.3 Aim and objectives of the Project

The aim of this project is to design and assemble a stand-alone solar power system that can reliably power refrigeration and other essential loads in rural health centres, thereby enhancing drug preservation and improving healthcare delivery.

The Objectives are

1. Conduct a load analysis of essential medical equipment used in rural primary health facilities.
2. Determine the appropriate sizing of solar panels, batteries, charge controllers, and inverters based on calculated energy needs.
3. Design and assemble a complete off-grid solar system tailored to rural cold-chain requirements.
4. Test and assess system performance under realistic environmental and operational conditions.
5. Evaluate the system's cost-effectiveness, ease of maintenance, and long-term sustainability.

1.4 Relevance of the Project

This project contributes to national and global goals for clean, reliable energy access. Stand-alone solar systems have the potential to improve living standards, strengthen healthcare infrastructure, and reduce dependence on fossil fuels in underserved communities. The work aligns with the United Nations Sustainable Development Goal 7, which calls for universal access to affordable and sustainable energy.

By ensuring consistent power for medical refrigeration, the system directly improves vaccination outcomes, drug efficacy, and overall patient care. It also offers a scalable model that can be replicated across rural regions where cold-chain failures pose persistent challenges.

1.5 Scope of the Project

The scope covers the full process of designing, sizing, assembling, and testing a stand-alone solar power system for rural primary health centres. The emphasis is on ensuring reliable refrigeration for temperature-sensitive medical supplies, evaluating system performance, and demonstrating its practicality for long-term deployment in remote areas.

CHAPTER 2

LITREATURE REVIEW.

2.1 Refrigeration and Its Impact on the Health System

Refrigeration is critical for maintaining the potency of temperature-sensitive drugs, vaccines, and biological samples, thereby underpinning the integrity of health systems globally.

Inadequate refrigeration practices can lead to the degradation of essential medicines, rendering them ineffective and potentially harmful to patients (James et al., 2016).

The significance of refrigeration extends beyond healthcare, playing a pivotal role in the preservation and transportation of perishable foods, mitigating biological decay, and ensuring food safety for consumers (Lin et al., 2019; Mercier et al., 2017). In health systems, refrigeration is indispensable for maintaining the cold chain, an uninterrupted series of temperature-controlled environments that ensure vaccines and other biologicals retain their potency from manufacture to administration. The disruption of cold chains, often exacerbated by supply chain vulnerabilities, can have dire consequences, leading to a decline in vaccine effectiveness and increased susceptibility to preventable diseases (Chu et al., 2022). The failure to maintain appropriate temperatures during storage and transportation can compromise the stability of vaccines, reducing their ability to elicit a protective immune response (Khan et al., 2024). Effective refrigeration strategies are thus essential to minimize microbial growth and maintain the quality and extend the shelf life of perishable products (Aung & Chang, 2013). Furthermore, proper refrigeration is crucial in hospitals and clinical settings for preserving blood samples, tissues, and organs intended for transplantation.

Recognizing these critical roles, this chapter seeks to provide a comprehensive review of refrigeration’s impact on the health system. It explores refrigeration as both a technical and conceptual necessity within healthcare infrastructure, examines its broader significance beyond pharmaceutical preservation, and evaluates solar-powered refrigeration as a practical and sustainable solution for improving cold chain reliability in rural and underserved areas. Given the challenges faced in regions with unreliable electricity supply, particularly in developing countries, solar technology is highlighted as a viable pathway for strengthening health systems and ensuring equitable access to safe and effective medical products.

2.1.1 Electricity Access and Power Reliability Challenges in Nigeria

Nigeria faces persistent challenges in expanding electricity access and ensuring reliable power supply, particularly in rural areas where grid infrastructure is limited. Efforts to increase electrification have progressed slowly, and a significant portion of the population remains without dependable electricity (Ohiare, 2015). The disparities between urban and rural access reflect systemic issues in the Nigerian power sector, including outdated infrastructure, inadequate distribution networks, and financial constraints that hinder expansion and service quality. These challenges limit not only basic electrification but also the ability of communities to benefit from modern services, economic activities, and social development.

Moreover, even among those with access, electricity supply remains highly unreliable, with grid-connected households receiving on average only about 6.6 hours of electricity per day, reflecting persistent challenges in Nigeria's energy sector (Nigeria Residential Energy Demand-Side Survey Report, 2024).This presents a difficult situation for the medical infrastructures in Nigeria especially those in rural areas where consistent electricity is essential for health service delivery. Facilities often lack backup power systems, leaving critical health equipment including refrigeration units non-functional during power outages.

2.1.2 Impact on Drug and Vaccine Potency

The consequences of unreliable electricity are especially severe when it comes to the storage and preservation of temperature-sensitive pharmaceuticals. A two-year field study observed that essential medications such as ampicillin, penicillin G, erythromycin, and chloroquine experienced a loss of more than 10% of their active components when kept in rural tropical environments, largely as a result of elevated temperatures and insufficient storage facilities (Hogerzeil et al., 1992).

These findings underline how inadequate refrigeration directly undermines drug stability and effectiveness. In rural healthcare settings, where ambient temperatures are consistently high and refrigeration capacity is limited, medicines risk becoming therapeutically ineffective or even harmful.

2.1.3 The Cold Chain and Vaccine Efficacy

Maintaining the cold chain is vital for maintaining the efficacy of vaccines. Vaccines require constant storage within controlled temperature ranges typically between 2°C and 8°C or at even lower temperatures to preserve their effectiveness throughout transportation and storage in healthcare facilities (UNICEF, 2021).

In health systems a cold chain describes the uninterrupted, temperature-controlled pathway from vaccine manufacture to patient administration

Disruption of cold chains, often caused by unreliable electricity and inadequate refrigeration infrastructure, can result in vaccines losing their potency. This, in turn, leads to reduced vaccination effectiveness, potential disease outbreaks, and wasted healthcare resources. UNICEF (2021) emphasizes that a break in the cold chain at any point from production to administration can compromise vaccine quality, posing serious public health risks.

A multi-state study conducted in India observed that vaccines were stored at temperatures exceeding 8 °C for approximately 6.6% of the monitored period, with continuous temperature excursions lasting longer than 45 minutes in 6.4% of cases. These conditions have been shown to compromise vaccine antigen stability and reduce immunological potency (Agarwal et al., 2017). Similarly, Jaffar et al. (2019) reported that inactivated oil-based vaccines exposed to 36 °C for 30 days experienced a statistically significant decline in serological potency ($p < 0.05$) compared to vaccines stored under standard refrigeration conditions at 4 °C.

A wide range of pharmaceutical products require stringent low-temperature storage to preserve their chemical integrity, therapeutic efficacy, and patient safety. These temperature-sensitive pharmaceuticals include vaccines, insulin products, biologics such as monoclonal antibodies, blood products, and certain chemotherapeutic agents (World Health Organization, 2015; Centres for Disease Control and Prevention, 2021; United States Pharmacopeia, 2023).

Vaccines are among the most critical products dependent on reliable cold chain systems. According to the CDC (2021), most vaccines must be stored within a temperature range of 2°C to 8°C. Some vaccines require even stricter temperature controls: for example, the Pfizer-BioNTech COVID-19 vaccine necessitates storage at ultra-low temperatures of approximately −70°C to preserve its mRNA-based formulation (European Medicines Agency, 2021).

Biologic medicines, including monoclonal antibodies, recombinant proteins, and gene therapies, are also highly temperature-sensitive. Exposure to inappropriate storage conditions can lead to protein denaturation or aggregation, rendering the product ineffective or immunogenic (Rathore & Rajan, 2008).

Insulin, essential for diabetes management, must be kept refrigerated to prevent degradation. The International Diabetes Federation (IDF, 2019) specifies that unopened insulin should be stored at 2–8°C. After opening, insulin can remain at controlled room temperature, but prolonged exposure to heat can reduce its potency, particularly in hot climates (World Health Organization, 2015).

Blood products such as red blood cells, plasma, and immunoglobulins require storage at specific temperature ranges to maintain safety and efficacy. For example, red blood cells are generally stored between 1°C and 6°C, while frozen plasma must be kept at −18°C or lower (World Health Organization, 2015).

Certain chemotherapeutic agents, such as asparaginase and temperature-sensitive immunotherapies, also demand strict cold storage to maintain stability and ensure therapeutic effectiveness. Loss of drug potency due to improper storage conditions can significantly impact treatment outcomes in oncology patients (United States Pharmacopeia, 2023).

These examples underscore the essential role of low-temperature storage infrastructure within healthcare systems, emphasizing the need for reliable and resilient cold chain solutions.

2.2 Refrigeration Principles of Operation

Before get into the fundamentals and principles of refrigeration, we have a few basic terms we must look at:

A). Heat is a form of energy transferred, due to variation of temperature levels, from one point to another. Heat is a type of energy which can neither be created nor destroyed.

Heat energy can also be gotten or produced as a byproduct of other forms of energy. Another important point to note about heat is that it travels in only one direction, which is from a warmer point to a cooler point.

B). Cold can be described as the absence of a significant amount of heat energy in a body/vessel. Another definition can be regarded as “the total absence of heat in a body”. There is no process existing yet, to achieve an absolute zero temperature, which is the total absence of heat energy in a body. Theoretically this temperature is pegged at 459.69 degrees below zero on the Fahrenheit scale, and on the Celsius scale 273.3 degrees below zero.

C). Refrigeration, on the other hand, refers to the removal of unnecessary/unwanted heat, from a body, vessel or space, to another vessel, body or space. Removal of heat reduces the temperature of the latter and this is achievable using ice, snow, cold water/solid or a mechanical refrigerator.

D). Mechanical refrigeration, is the arrangement of various mechanical devices/components, which altogether are capable of creating a cold environment for the purpose of heat removal and reduction.

E). Refrigerants are liquids, composed of chemical compounds, which are capable of compressing/condensing and then permitted to expand into gas/vapor as they cycle through the refrigeration system.

The refrigeration cycle is generally based on the idea that liquid when expanding into a gas absorbs heat from the surroundings on evaporation. This can simply and easily be described with a simple experiment, whereby we dip our palm in water and then hold it up. It further starts to feel cooler than the other, especially when exposed to some air movement, as the water starts to evaporate from the surface of our palm. This generally makes our palm feel cooler, as simple as this experiment, it describes and proves this thesis. The process is simple, as the liquid/refrigerant evaporates, it removes heat. The boiling point of refrigerants are generally much less than that of water, this gives the ease of evaporation and temperature reduction.

F). Refrigeration system fundamental components

The main job of the refrigerant is to remove unwanted heat and dump it and dump it in another area/substance. To achieve this, the refrigerant is pumped through a closed system, otherwise, the refrigerant would be used up by the surrounding system or atmosphere and the main purpose wouldn't be achieved and the refrigerant would end up getting wasted. To prevent this, the refrigerant had to be pumped through a closed system, allowing it to be used over and over again as it goes through the cycle removing unnecessary it and dumping it. The closed system also serves a second purpose as it prevents the refrigerant from contamination and also controls its flow, due to the fact that the refrigerant exists as a liquid in some parts of the system, and a gas/vapor in other parts.

2.3 Principles of Refrigeration ~ Chiller Efficiency &Condensation

Now we're going to talk more about the principles of refrigeration and reiterate some of the common terms we discussed previously and shed some more light to their working principles and operations.

One of the most important of storage and preservation, is refrigeration, whether it is in drugs, food, meat, volatile liquids or temperature sensitive materials, refrigeration is a very crucial aspect of their storage. Due to this cause, we need to know how to use the refrigeration system to maintain these products in good condition.

To achieve this, we must understand the principles of refrigeration and how the various components work. We must also understand how, by operating the system properly, we can maintain the efficiency of the chilling operation and control problems such as condensation. It is important to note that refrigeration does not introduce any foreign body/substance, to the substance which is to be refrigerated. Furthermore, for temperature sensitive materials, it also keeps them below or at the temperature which they need to be maintained at, to avoid destruction.

The Refrigeration system

There are several different methods used to achieve the cooling effect of a refrigeration system, such as ice, liquefied gas, absorption, etc. But throughout the drug and food industry, the method primarily used is the mechanical vapor compression system. The essential components of this system are: refrigerant, compressor, refrigerant expansion device, condenser and evaporator. Some of these as we have mentioned before and all others mentioned, make up a simple vapor compression system.

The refrigeration cycle can be explained by the pressure or enthalpy diagram (FIGURE 1). Enthalpy is a property of a system which relates to the system’s internal energy. Enthalpy is derived from a Greek word, which signifies “warm”. Starting at Position 1 on the diagram, vapor at a significantly low temperature and pressure, is brought into the compressor. The compressor, at work, raises the pressure at temperature of the vapor (Position 2). The vapor at high pressure and temperature then moves to the condenser where it is cooled, losing its latent heat, so that it condenses back to its liquid form (Position 3). The high-pressure liquid from the condenser is then expanded through an expansion valve (position4). At this level the refrigerant is currently at a low pressure and is mostly liquid. It has a low boiling point due to the low- pressure. When it moves into the evaporator coils, the liquid refrigerant starts boiling, taking in the necessary latent heat of evaporation from the surrounding air. The vapor at low pressure and low temperature then moves to the suction side of the compressor (Position 1) and the whole process goes on and on, just like that. The pressure/temperature conditions at the condenser, and the evaporation, are the two most important conditions in the entire cycle.

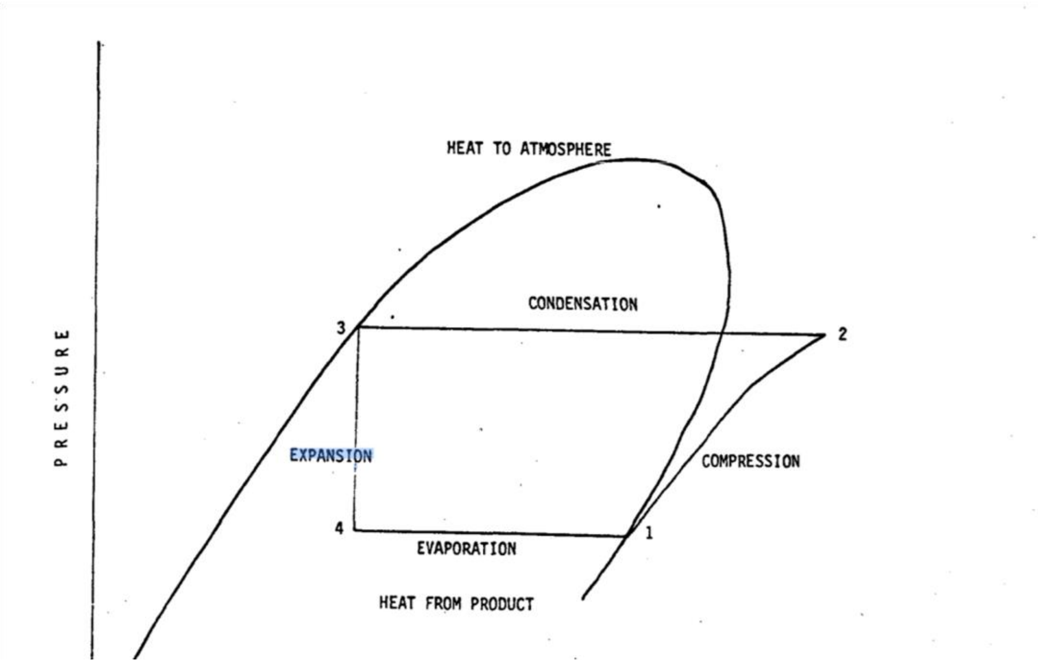


Figure 1 Pressure/Enthalpy Diagram for Vapor Compression cycle

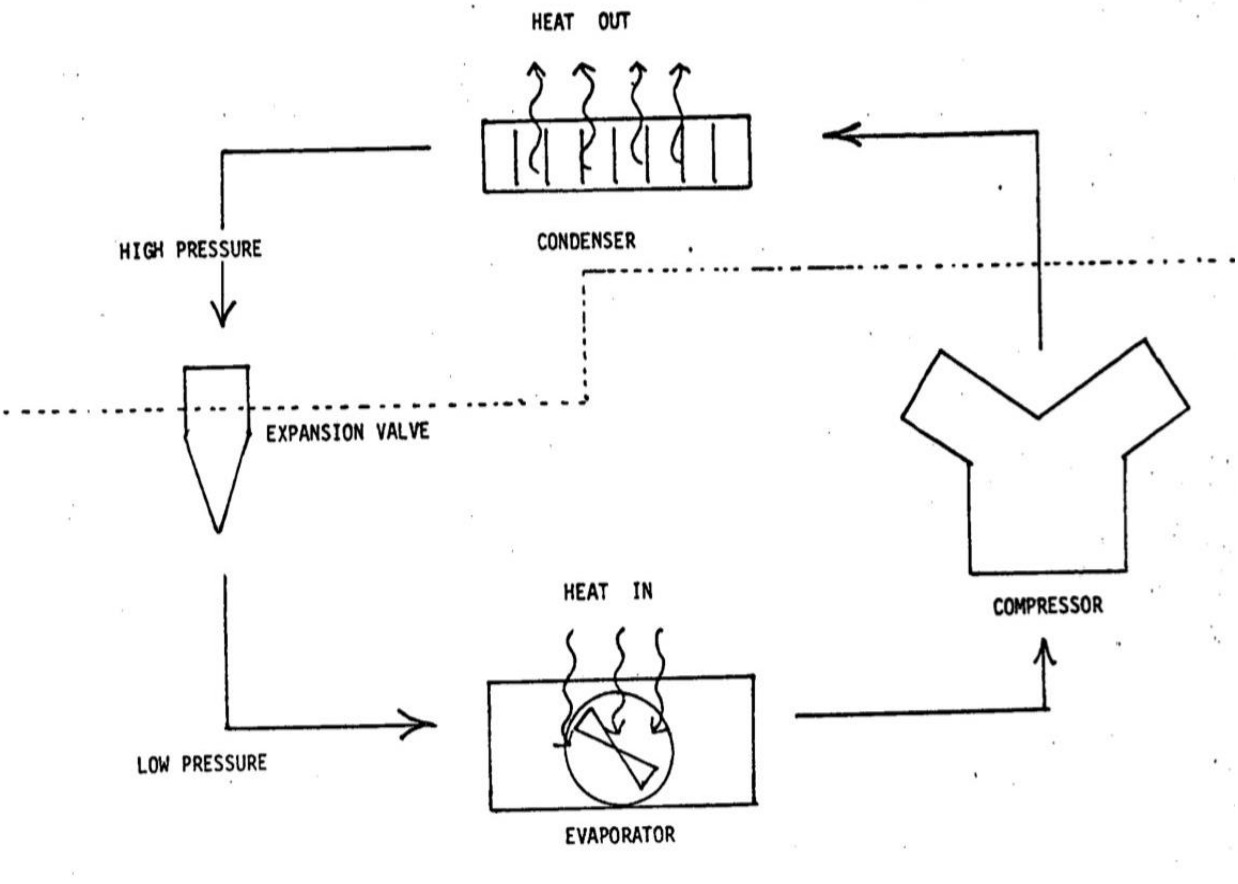


Figure 2 The Vapor Compression Refrigeration Setup

2.3.1 The Refrigerant

The refrigerant, just as we talked about before, is the working fluid of the cycle. It vaporizes as it takes in (absorbs) heat, and condenses as it dissipates heat to the environment. The primary requirements of a refrigerant are as follows:

Possessions of high latent heat of vaporization

A low specific heat of liquid

Relatively high vapor density

Safety

Low financial cost

Number 1 and 2 both have direct effect on the refrigeration per given mass of refrigerant circulated.3 takes its toll on the size of the compressor needed for a particular refrigeration process.

Ammonia is the most commonly used refrigerant, because it checks most of the boxes. Smaller systems usually use Freon.

The downside of ammonia is its toxicity; it has a strong pungent smell and prolonged exposure to its fumes is fatal to human life. There are little to no risks in its use, where proper guidelines and handling processes are followed.

2.3.2 The Compressor

The major energy input in the refrigeration cycle comes from the compressor. The amount of energy needed from the compressor by the system, is directly linked to the volume of refrigerant circulated and the following increase in pressure needed to compress the refrigerant vapor lowering and increasing the temperature in the evaporator and condenser respectively, leads to greater pressure difference between them, this leads to greater power demand from the compressor. Lowering temperature in the evaporator, leads to the increase in volume per unit weight of the refrigerant. This in return reduces the refrigeration capacity of the compressor.

2.3.3 The Condenser

On the compression of vapor, the temperature and pressure increases. It is then moved to the condenser, where this hot, high-pressure vapor cools down and loses its latent heat. It then returns to liquid at high pressure.

In the food industry, the evaporative condenser is the most common. Due to the fact that water sprays help with cooling, its capacity is directly affected by ambient wet bulb temperature. In major parts of Australia, especially at times of high ambient temperatures, the wet bulb temperature is to a large amount higher than the dry bulb temperature. This gives an evaporative condenser an upper hand over the air-cooled condenser. The two types of condensers both need free distribution of air over their surfaces for cooling. Normally, condensers should be positioned well, clear of buildings and structures which could prevent or cut short air flow.

For evaporative condensers, a good supply of water is necessary for its optimum operation. As water is removed continuously, scale would be fanned out by continuous precipitation of salt. If this scale proceeds to build up, the rate of transfer of heat would decline, causing an increment in the refrigerant temperature. This same issue is pertinent in air cooled condensers, if the coils or fins are left to become soiled with rubbish of any sort. Effective cooling can then only be kept constant, when the compressor is maintained at high pressure, which would result in a highly increased power use. It is therefore pertinent that the condenser must have enough cooling to dissipate the heat extracted by the evaporator as well as the heat added by the compressor.

2.3.4 The Expansion Device

The expansion device keeps the pressure difference between the evaporators and condensers, which is pertinent for the normal operation of the system. It allows expansion of refrigerant, from high pressure, to a lower pressure, in the system.

2.3.5 The Evaporator

Coming from the expansion device, the refrigerant, which is currently under low pressure, is steamed through evaporators, made up of coiled tubes, whose surface areas are increased in addition to fins. The refrigerant removes heat from the air and turns it into vapor. Fans are placed to blow air over the finned tubes. The rate of transfer is thereby increased and the necessary air distribution pattern is achieved on the chiller. The extent to which the evaporator cools is dependent on the surface area of the coils, the difference in temperature between the refrigerant and air being cooled, and the rate of heat transfer through the coil.

2.4 Technical Overview of Solar Photovoltaic Systems

A solar panel is a device that converts sunlight into electrical power by using photovoltaic (PV) cells. Photovoltaic cells are made of materials that produce excited electrons when exposed to light. Photovoltaic cells produce direct current which can be stored in batteries.

Photovoltaic cells consist of the following:

Solar panels

Inverter

Controllers

Meters

Trackers

2.4.1 Solar Panel:

This is the part of the solar system that collects sun light and converts it to electricity.

It is made of two layers of semi conducting materials, usually silicon, one layer is positively charged and the other is negatively charged.

The solar panel consist of solar cells which are used in the generation of electricity through what is known as photovoltaic effect and it is the core component of the solar panel.

The solar cell is the basic building block of the solar panel; it is responsible for converting sunlight directly into electricity.

The solar cells must be protected from moisture and mechanical damage. The cells are usually connected electrically in series, one to another to the desired voltage and then in parallel to increase current.

The power, voltage and current of the solar system depends on the amount sun light and the electrical load connected to the solar system. Most of the times the solar panels are always mounted on the roofs of buildings to get maximum supply of sunlight.

When sunlight strikes the solar cell, photons are absorbed and excitation of electrons takes place. Electrons break free during excitation leaving behind holes (positive charges). The electrons are the pushed to the n-side and holes to the p-side. The movement of electrons in the solar panel causes direct current to produced

2.4.2 Inverter:

The core function of the inverter is to convert DC to AC; it is connected to the solar panel so it can extract direct current. The helps to regulates voltages.

Inverters optimize the performance of solar panels by adapting to varying sunlight, by managing and adjusting the output, they help adjust the output, the power much power is generated, without an inverter there will be a fluctuation in voltage because voltage depends on the intensity of sunlight.

Inverters provides real time data, allowing for easy monitor of the solar systems, detect performance issues, and manage maintenance effectively. This feature adds transparency and confidence in solar investment.

Inverters manage the charging and the discharging of batteries, enabling stored energy to be used during peak hours or power outages.

For a stand-alone system, the inverters are selected based on the input battery voltage, maximum load.

An inverter should be installed in a controlled environment because high temperature and excessive dust will reduce lifetime and may cause failure. The inverter should not be too far from the batteries to avoid resistive lost in the wires.

2.4.3 Batteries:

They are used to store excess energy from the photovoltaic panel to be used at night or when there is no longer energy input. The battery provides steady power.

Secondary batteries are used in standalone system because they can be recharged once used up by passing current in the opposite direction through them. Battery storage capacity is rated in ampere hours.

2.4.4 Types of Batteries

Lead acid batteries

Alkaline batteries

Batteries used in photovoltaic system are potentially dangerous if improperly handled, installed, or maintained. Dangerous chemicals, heavy weight and high voltages and currents are potential hazard and result in electric shock, burns explosion or corrosive damage to a person or property.

The lifetime of the solar battery depends on factors such as charge and discharge rate, depth of discharges, number of cycles and operating temperatures. Usually lead acid type of battery last of up to 10 years. Nickel candium batteries will generally last longer when operated under similar condition and may operate satisfactory for more than 13years under optimum condition.

2.4.5 Controller:

Controllers are only used in a stand-alone system; the function of the controller is to overcharging and excessive discharge.

Over charging can boil the electrolyte from the battery and case failure.

Types Of Charging Controller

There are two types of charge controller:

Shunt charge controller: contacts opens when the battery is charging and closes when the battery is fully charged.

Series charge controller: contacts opens when the battery voltage reaches the high voltage level. There are small and inexpensive and have a greater load handling capacity than shunt type controllers.

Selection Of Charge Controllers

The controller voltage must match the solar panel voltage

The controller must be able to handle maximum current produced by the solar panel

The controller must not interfere with the operation of the inverter

System Meter

This unit measure the charge of the battery, production of electricity from solar panels and amount of electricity in use. It is possible to operate a system without a system meter, though meters are strongly recommended.

2.4.6 Sizing A Standalone Solar Panel

For a standalone photovoltaic system, the panel produces energy, while the battery stores the energy produced.

It is important to consider the sizing of a standalone solar panel in order to balance between the energy supply and the energy demanded (in this case a cooling system)

In order to size the stand-alone solar system, the following steps are taken into consideration:

Estimating the electrical load (cooling system)

Sizing and specifying the inverter that can be used

Sizing and specifying batteries that can store enough energy

Sizing the solar panel

Specifying the controller to be used

2.4.7 Estimating the Electrical Load:

The power required by the cooling system can be measured or obtained from the label on the back of the appliance (nameplate) which list the watt in other to get the following information of the load

Rated power – running wattage when the compressor is on

Startup surge – brief high-power draw when the compressor starts

Energy consumption of the load

2.4.8 Battery Sizing

Batteries for standalone systems are sized to store energy produced by the solar panel for the load required. The total amount of rated battery capacity required depends on the following

Autonomy days: the number of consecutive days the battery must power the load without recharging from the solar panel

Depth of discharge (DoD): the maximum percentage of battery capacity that can be safely used

Temperature and discharge rate: cold temperatures reduce battery capacity, while high discharge rates decrease efficiency.

System losses and efficiency: energy losses in inverters, charger controllers, and wiring must be accounted for.

System voltage determines the number of battery cells needed in series.

2.4.9 Sizing of Solar Panel

The solar panel must be properly sized to properly sized to reliably meet the energy demands of the connected loads.

Key factors affecting the size of solar panel are:

The system should be designed based on the month or season with the lowest solar irradiance to load ratio to ensure year-round operation

Factors such as temperature effects, and inefficiencies in wiring, charge controllers, and inverters reduce actual output.

Increasing the solar panel or battery storage enhances system reliability, ensuring uninterrupted power during low sun periods.

2.4.10 Selecting an Inverter:

This unit helps to convert DC into AC. The inverter must have the same voltage matching as the battery. The inverter is rated in watts. The input rating of the inverter should never be lower than the total watt of the appliance.

2.5 Standalone Photovoltaic Systems

A standalone photovoltaic system is also known as an off grid photovoltaic system; it has no connection to an electricity grid. A simple standalone PV system is an automatic solar system that produces electrical power to charge banks of batteries during the day for use at night when the sun's energy is unavailable. The kind of batteries used are deep cycle batteries because they are rechargeable. But they are designed to be repeatedly discharged almost all the way down to a very low charge.

A charge controller ensures that the maximum output of the solar panels is directed to charge the batteries without over charging or damaging them.

An inverter helps in the conversion of DC into AC power for use in in appliances.

A standalone system is ideal for the electrification of rural areas or offshore sites that do not make use of the power grid.

2.5.1 Benefits of A Standalone System

Constant power supply

No connection to power grid

Works in rural areas

Does not require payment of electricity bill

No issues relating to over current or over voltage

2.5.2 Draw Backs of Standalone System

Can run out of power is not sufficient amount of sunlight during the day

Initial cost can be very expensive

Load can be limited

2.5.3 Maintenance

PV has no recurring fuel cost, and it is promoted as a simple energy technology that is durable and relatively maintenance free case it has no moving parts. However, designers should ensure that the installations allow for easy inspecting, repairing, cleaning and replacing components.

Efficiency: Efficiency does degrade over time due to several factors. Inefficiency is most times caused by climatic conditions, such as dust and heat which similarly comprise the quality and efficiency of other building systems.

Degradation of PV panels typically occurs on the cellular level and many studies place the rate at 0.5-0.7% annually.

Cleaning: Regular cleaning of PV panels is a certain limitation. For the standalone system the PV panel should be cleaned very 2 weeks.

Flammability: PV panels are flammable and in case of fire, they can get burnt easily. During design of PV panels fire risk mitigation is typically carried out.

Warranties And Cost: PV panels should be able to withstand severe weather, including extreme heat, cold and hailstorms.

2.5.4 Cost of A Solar Panel

Cost of a solar panel depends on several factors like:

System configuration

Equipment options

Labor cost and financing cost

Size of the standalone system

Power that will be produced by the standalone system

Generally, the initial cost of installing a solar panel is very high, but with a solar system you can save on the purchase of electricity from the grid.

Solar energy is one of the purest forms in which energy can be generated, as it does not cause any environmental problems such as pollution and waste. Solar energy has long been used directly as a source of thermal energy. Beginning in the 20th century, technological advances have increased the number of uses and applications of the sun's thermal energy and opened the doors for the generation of solar power.

2.6 Case Studies on Solar Refrigeration in Healthcare Systems

Solar-powered refrigeration has emerged as a key solution for maintaining vaccine integrity in off-grid and energy-insecure regions. Several countries have implemented solar refrigeration systems in healthcare facilities with notable improvements in vaccine availability, cold chain reliability, and immunization outcomes.

In Kenya, the Ministry of Health collaborated with partners such as UNICEF and Gavi to introduce Solar Direct-Drive (SDD) vaccine refrigerators to rural clinics. These battery-free fridges are well-suited to areas with limited electricity. According to UNICEF (2021), this initiative significantly improved vaccine availability and reduced cold chain failures. The project also enabled broader use of vaccines like HPV and rotavirus, which are more temperature-sensitive.

Uganda's Ministry of Health, with support from the World Health Organization, undertook a similar expansion of solar refrigeration in remote areas. A WHO report (2021) indicates that these installations supported expanded immunization efforts, particularly in northern districts. Clinics reported more consistent vaccine storage and fewer stock-outs, contributing to increased patient coverage.

Bangladesh implemented one of the most extensive solar refrigeration rollouts under its Expanded Programme on Immunization (EPI), with support from Gavi’s Cold Chain Equipment Optimization Platform. According to Gavi (2020), over 5,000 health posts received solar-powered vaccine refrigerators, resulting in improved vaccine potency and reduced waste across rural areas.

In Nigeria, several pilot initiatives have utilized solar refrigeration to support vaccine cold chains in states such as Kano and Bauchi. UNDP Nigeria (2022) reported that these installations improved maternal and child health outcomes by enabling more reliable vaccine availability. These pilots also informed strategic health policies under Nigeria’s National Strategic Health Development Plan II.

Ethiopia, in partnership with PATH, Gavi, and the Ministry of Health, installed hundreds of solar-powered vaccine refrigerators in areas with frequent power interruptions. PATH (2021) noted that these interventions helped reduce immunization disruptions and enabled more predictable outreach. Temperature-monitoring tools integrated into the fridges allowed staff to track performance and respond to potential equipment failures proactively.

Overall, these case studies highlight the critical role of solar refrigeration in strengthening immunization systems in underserved settings. While specific outcomes vary, consistent trends include reductions in vaccine spoilage, enhanced outreach capabilities, and increased resilience of healthcare services.

CHAPTER THREE

3.1 Research/Project Design

This project presents a design implementation aimed at addressing the persistent challenges of refrigeration in rural healthcare facilities, particularly those affected by unreliable or non-existent grid electricity supply. The initiative focuses on the development, testing, and deployment of a fully functional solar-powered refrigeration system designed to maintain a stable internal temperature range of 2–8°C, which is essential for the safe storage of vaccines and other temperature-sensitive medical supplies.

This study was classified as a prototype development project, drawing on data from previous feasibility studies and real-time temperature monitoring. The objective is to establish an efficient and sustainable refrigeration model tailored to the specific climatic and infrastructural conditions of rural Nigeria, particularly Benin, Edo State, where the average daily solar radiation provides an estimated 4.5 peak sun hours (Njoku et al., 2022).

Although the current model is a proof-of-concept, the design methodology, energy calculations, and component integration are intentionally scalable, with the long-term goal of guiding broader implementation strategies in real-world health infrastructure. The prototype seeks to demonstrate the technical viability, energy efficiency, and reliability of off-grid solar refrigeration systems to support public health services in resource-constrained environments.

The proposed setup consists of the following:

A 60W AC refrigerator designed for vaccine and medical storage,

A 1kVA pure sine wave inverter to convert DC from solar to AC power,

A solar panel as the primary energy source,

One deep-cycle battery was used for energy storage during non-sunlight hours.

This setup was deliberately minimalistic to explore the threshold for a minimum viable solution, balancing cost, efficiency, and performance under rural conditions.

3.2 Key Objectives of the Design

The project is structured around the following objectives.

1. System Sizing and Load Matching
2. The solar panel and battery system were accurately sized based on real-time energy consumption data, ambient temperature fluctuations, and typical weather patterns.

To ensure optimal matching of power output and load demand, especially during critical periods, such as cloudy days or extended usage.

3. Inverter Compatibility Verification
   a) To assess the compatibility of the 1 kVA pure sine wave inverter with the 60 W AC refrigerator.
   b) To ensure smooth operation without voltage drops, overloads, or system instability.
4. Battery Capacity Testing
   a) The performance of a single deep-cycle battery was tested to store sufficient energy for overnight and low-sunlight operations.
   b) To identify discharge rates, depth of discharge (DoD), and recovery during peak sunlight hours.
5. Temperature Monitoring System Integration
6. Real-time internal temperature logging equipment was deployed inside the refrigerator. This ensures that the system consistently maintains the target range of 2–8°C and provides performance data for further analysis.

3.3 System Sizing Calculations

This section details the energy demand estimation, solar panel sizing, battery capacity calculation, and inverter selection, all tailored to the load requirements of a 60W AC refrigerator operating under typical environmental conditions in Benin, Edo State, which receives approximately 4.5 peak sun hours per day.

3.3.1 Load Estimation

The estimated load of an appliance is calculated by multiplying its power rating by the number of hours it operates daily (U.S. Department of Energy, 2010).

Refrigerator Power Rating = 60W

Assumed Daily Operational Time = 24 hours (continuous)

$$E\_load = Power \times Time = 60\,W \times 24\,h = 1440\,Wh/day$$

3.3.2 Solar Panel Sizing

The first step in sizing solar panels is to obtain the average peak sun hours in the area where the panels are to be mounted. The concept of peak sun hours refers to the total solar energy received during a day, expressed as the equivalent number of hours at a full solar intensity of 1,000 W/m². This simplifies solar energy calculations by normalizing variable sunlight into a standardized unit, making it easier to size solar systems (Master, 2004).

From experimental data obtained in a study by Njoku et al. (2022), the average daily solar radiation for Benin City was found to be approximately 4.47 kWh/m²/day, which corresponds to about 4.5 peak sun hours (PSH). This value was based on a 20-year dataset collected from NASA and NIMET, representing typical solar availability in the southern geopolitical zone of Nigeria.

To calculate the solar panel size, the daily energy demand is divided by the number of peak sun hours and then adjusted for system inefficiencies, such as temperature losses, inverter efficiency, and other derating factors (University of Arizona Cooperative Extension, n.d.).

Solar Panel Size = $\frac{Eload}{peak\ sun\ hours}$

Solar Panel Size = $\frac{1440wh}{4.5}$ = 320W

3.3.3 Battery Sizing

Battery sizing is crucial for ensuring there is sufficient energy to run the equipment even when the energy from the sun proves insufficient. As such various factors are taken into consideration when choosing a battery, one of which is that the battery bank must be capable of storing enough energy to power the refrigerator for a designated autonomy period, typically 1-2 days in rural areas (SEI API, 2012; SEI, 2013; World Bank, 2014; WHO, 2018).

Another factor considered is the depth of discharge. Depth of discharge refers to the percentage of the battery's capacity that is used. For example, a 50% DoD means that half of the battery's capacity has been used. Deep-cycle batteries are designed to operate efficiently with higher DoD, but exceeding recommended DoD levels reduces lifespan. In this project, a DoD of 50% is used to balance longevity and energy availability (Battery University, 2015; Ecoflow, 2024).

Batter efficiency is also taken into consideration. A round-trip efficiency of approximately 85% was assumed for the battery storage system, reflecting typical performance of lead-acid deep-cycle batteries, which commonly exhibit energy losses of 15–25% during charge and discharge cycles, depending on age, temperature, and depth of discharge (Clean Energy Reviews, 2020; Mongird et al., 2021; Cole & Karmakar, 2023).

The required battery capacity was calculated using the formula:

Battery Capacity = $\frac{Daily\ Energy\ Load \times Days\ of\ Autonomy}{DoD \times Battery\ Efficiency}$

Substituting the values:

Battery Capacity = $\frac{1440 \times 1}{0.7 \times 0.85}$ = 2420.16 Wh

This means the system requires a minimum of 2420.1 Wh of battery storage to support one full day of operation without solar input. For a 12V system, this translates to:

Battery Capacity = $\frac{2420.1\,Wh}{12}$ = 201.6 Ah

This calculation follows industry-standard solar design practices (SEI, 2013; Clean Energy Reviews, 2020; NREL, 2024).

However, instead of the initially planned 200 Ah battery, a 12 V, 220 Ah battery was selected. This upgrade provides greater energy storage capacity, allowing the system to sustain the load for longer periods and operate more efficiently. The improved capacity enhances reliability during low-sunlight hours and represents a strategic investment to optimize system performance without significantly increasing overall cost.

3.3.4 Inverter sizing

The inverter is a critical component in this setup since the refrigerator operates on alternating current (AC), while the solar panel and battery provide direct current (DC). An inverter converts DC into AC at the appropriate voltage and frequency (Tennessee Tech University, n.d.; ScienceDirect, n.d.). Field measurements of refrigerator compressor performance indicate that power factors vary widely, from as low as 0.36 in older or poorly maintained units to values approaching 0.96 in newer models. On average, however, most refrigerators operate near a power factor of 0.65. For design purposes, engineers often adopt a nominal power factor of about 0.85 to account for the predominantly inductive nature of compressor loads while still providing a reasonable margin for efficiency considerations (Prayas, n.d.). In addition, fixed-speed compressor systems typically draw a transient inrush current at startup that can be roughly three times higher than the steady-state running current. These characteristic underscores the importance of selecting inverters with sufficient surge capacity to ensure stable operation during compressor startup events (Zilpe & Khan, 2015).

For a refrigerator rated at 60W:

- Running Power: 60 W
- Estimated Surge Power: 60 W × 4 = 240 W

Apparent Power (kVA) Calculation

The apparent power is calculated using the formula:

$$S\ (\text{kVA}) = \frac{Power\ (kW)}{Power\ Factor\ (pf)}$$

Where:

- Refrigerator running power, P = 60W = 0.06 kW
- Power factor (pf) = 0.85

$$S = \frac{0.06}{0.85} = 0.071\text{kVA}$$

Startup Surge Requirement

Refrigerators typically draw 3 times their running power during compressor startup.

Surge = 0.071 × 3 ≈ 0.211 kVA

The inverter selected for this design is a 1 kVA pure sine-wave inverter, which comfortably meets both the running and surge requirements of the refrigerator.

3.3.5 Summary of Sizing Results

The system sizing analysis yielded the following results:

- Daily Load Demand (E_{liad}): 1440 Wh/day, based on a continuous 60 W refrigerator load.
- Solar Array Capacity: Approximately 320 W of installed PV capacity, derived from an average of 4.5 peak sun hours (PSH) in Benin City, with allowances for system losses and derating factors. However, although a 320 W panel could adequately sustain the load, a 550 W monocrystalline panel was selected instead to provide sufficient power for both running the load and charging the battery

simultaneously, thereby improving system efficiency and energy availability.

- Battery Storage Requirement: A minimum of 2420.1 Wh, corresponding to a 12 V, 201Ah deep-cycle battery bank. This value provides one day of autonomy, accounting for a depth of discharge (DoD) of 70% and an assumed round-trip battery efficiency of 85%.
- Inverter Specification: A 1 kVA pure sine wave inverter was selected. This rating ensures adequate capacity for the refrigerator's 60W continuous running load while accommodating startup surge requirements of up to 240 W.
-

The above configuration represents a minimum viable system capable of maintaining a stable refrigeration environment (2–8 °C) under the climatic and infrastructural conditions of rural Benin.

3.4 Design Considerations

The technical viability of the solar-powered refrigeration prototype depends on more than precise load and component sizing; practical constraints must be accounted for to ensure real-world applicability. The following design considerations—site solar potential, budgeting, component access, and cooling reliability—frame not only what is possible, but what is sustainable and dependable under rural healthcare conditions.

3.4.1 Site Selection

Benin City, Edo State, was selected for this study because of its high solar radiation potential, consistent peak sun hours, and infrastructural context that mirrors many rural healthcare settings in southern Nigeria. Local meteorological data and solar profiling (Njoku et al. 2022) show that average daily solar insolation in Benin City offers about 4.39 kWh/m²/day in summer and similar values in other seasons, implying strong opportunities for photovoltaic energy capture.

Additionally, Nigeria’s broader solar irradiation maps (such as those accessible via the World Bank / Global Solar Atlas) indicate that many areas of Edo and its environs lie within zones favourable for off-grid solar generation, with Global Horizontal Irradiance (GHI) levels that support system designs aiming for continuous operation even during less favourable weather. Key local site factors considered include roof orientation, shading (trees, neighbouring structures), ambient temperature, and airflow around the installation site—these affect PV panel performance and thermal efficiency. Tilt angles are aligned near local latitude, and orientation is optimized to maximize output year-round. Together, these criteria help ensure that PV output sufficiently matches load demands, especially given that the system is designed for low-sun-hour periods as well as peak periods.

3.4.2 Budget Constraints

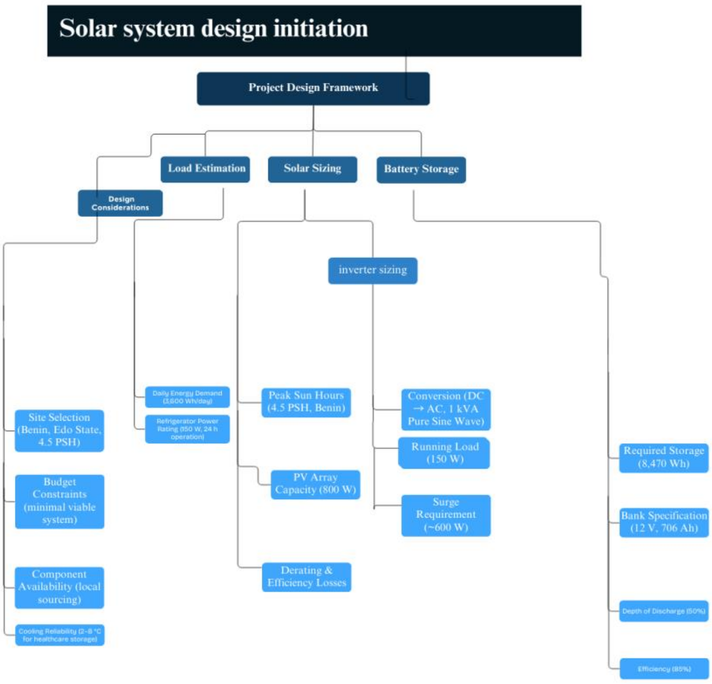
Cost remains one of the defining limits for deployment in rural healthcare, where funding is often limited and the return on investment must be clearly justified. This prototype is deliberately minimalistic: components include one 60W vaccine-grade refrigerator, an 550W PV array, a 12 V/220 Ah deep-cycle battery bank, and a 1 kVA pure sine-wave inverter. The design tries to strike a balance—providing enough capacity for reliability and redundancy (e.g., surge during compressor startup, one-day autonomy) while avoiding over-sizing that could escalate capital costs or make maintenance and deployment financially unsustainable. Oversizing could raise initial procurement, shipping, and installation costs substantially; under sizing, by contrast, risks system downtime or inability to maintain required refrigeration temperatures. Thus, cost-performance-trade-offs are emphasized throughout component selection and system layout.

3.4.3 Component Availability

A critical constraint in many parts of rural Nigeria is that highly specialized or niche solar and refrigeration parts are not reliably available. Imported components often come with high shipping costs, longer lead times, and issues of compatibility or counterfeit risk. To mitigate these, this project prioritizes components that are either already in the local/regional supply chain or are standardized enough that replacements or repairs are feasible—such as lead-acid deep-cycle batteries, pure sine wave inverters with common specifications, and refrigerator units compliant with WHO or CDC vaccine storage guidelines. This enhances maintainability, reduces lifecycle costs, and increases the probability that the system can be repaired or scaled locally without needing specialized external support.

3.4.4 Cooling Reliability in Healthcare Applications

For vaccine storage and other temperature-sensitive medical supplies, maintaining an internal temperature between 2 °C and 8 °C is non-negotiable (PAHO/WHO; CDC



Vaccine Storage & Handling). Any deviation above or below this range risks compromising vaccine potency, safety, or efficacy. To ensure reliability:

The system has been sized with one day of autonomy, assuming 70% depth of discharge (DoD) and an estimated round-trip storage efficiency of ~85% to safeguard during periods of reduced sunlight or unexpected usage.

A 1 kVA inverter is chosen to accommodate both the continuous running load (60 W) and transient surge (≈240 W) during compressor startup, so that voltage drops or harmonics do not compromise refrigeration performance.

Real-time temperature monitoring is integrated so that healthcare staff can track internal fridge temperatures, document deviations, and respond quickly.

The design aligns with global cold chain and vaccine storage standards, such as those laid out by WHO and PAHO, ensuring that the system is not only technically sound but also compatible with regulatory and health system oversight.

3.5 Implementation Process

The implementation process for the standalone solar power system, followed a structured approach to ensure safety, efficiency, and reliability.

Cable and Fuse Sizing

We size cables and fuses based on the maximum current they will carry. We use the standard formula: $I = P / V$. We aim for a maximum voltage drop of <3%.

1. Solar Array to Charge Controller:

Max Current: 60W / 12V = 5 A

Cable:12 AWG (2.5mm^2) is sufficient for this current over typical short distances (<10ft). For longer runs, use 10 AWG (4mm^2) to minimize voltage drop.

2. Charge Controller to Battery:

Carries the same current as the solar array. Use the same specs as above.

Cable: 12 AWG (2.5mm²) or 10 AWG (4mm²).

3. Battery to Inverter (or DC Load):

This is the most critical connection. The inverter draws a very high current.

For a Fridge (60W):

Max Current: 40W / 12V = 3.3 A (Running), but compressor startup surge can be 3x higher (~10A).

Fuse: 15A DC fuse.

Cable:14 AWG (1.5mm²) is electrically sufficient, but 12 AWG (2.5mm²) is more robust.

For an AC System with a 500W-800W Inverter:

Inverter Max Draw (assuming 90% eff): (500W / 0.9) / 12V = 74.3 A

Fuse: 100A ANL fuse on the battery terminal.

Cable: 6 AWG (10mm²) is the minimum recommended size for this current to prevent overheating and voltage drop. 4 AWG (16mm²) is better.

4. Inverter to AC Fridge:

Standard household wiring. A simple 16 AWG (1.0mm²) power cord is sufficient for a 60W device

Wiring Connections

Specific wiring procedures were meticulously followed:

The solar panel was connected to the charge controller using 4 mm² copper wires, with strict adherence to polarity (positive-to-positive and negative-to-negative) to prevent potential damage to the controller.

A single 12 V, 200 Ah deep-cycle battery was connected to the charge controller output terminals to store the generated energy. The connection employed 16 mm² low-resistance cables to minimize power losses and safely handle the expected current flow.

The battery's DC output was then connected directly to the 1 kVA, 12 V inverter input terminals.

Finally, the AC load (60 W refrigerator) was connected to the inverter's AC output terminals for operation.

Safety Features:

Safety was a paramount concern during installation. The system incorporated several protective features:

Fuses and Circuit Breakers:

The charge controller itself acts as a primary safety device, providing protection against overcharging, over-discharging, and reverse current flow from the batteries to the panels at night (Ezugwu, 2012). Additionally, appropriate fuses or DC circuit breakers were installed in line between the battery and the inverter to protect against short circuits and excessive current draw that could cause overheating and fire hazards.

Proper Grounding:

The entire PV system, including the panel frame and the inverter chassis, was properly grounded to the earth. This is a critical step to protect against the threat of electric shock from induced surges, such as those from lightning strikes (Ezugwu, 2012).

Environmental Protection:

Panel Mounting:

The solar panel was mounted on the roof, which was determined to be the most convenient and appropriate location. It was installed above and parallel to the roof surface with a several-inch stand-off gap. This gap is crucial for cooling purposes, as module output power reduces significantly as temperature increases (Ezugwu, 2012). The 200W system required approximately 40 square feet of unobstructed area.

Weather Sealing:

Particular attention was paid to the weather sealing of all roof penetrations made for mounting brackets and cable conduits to prevent water leaks and subsequent damage to the roof structure.

CHAPTER 4

RESULTS AND ANALYSIS

4.1 Preface

This chapter details the quantitative outcomes and subsequent technical analysis resulting from the design, implementation, and field testing of the standalone solar photovoltaic (PV) system. The system was engineered specifically to ensure reliable drug preservation through refrigeration in remote, rural environments. The primary function of this chapter is to present verifiable data, validate the initial system design assumptions, and objectively assess the operational performance against established criteria.

The chapter commences with the system specifications, providing the precise technical parameters for the solar panel, tubular lead-acid battery, pure sine wave inverter, and charge controller. This section also lists the characteristics of the Hisense 90 L refrigeration unit, which constitutes the critical load.

Following the specifications, the empirical measurements and analytical calculations are presented. This includes measured data on solar panel voltage and current output variation, charge controller efficiency, and the battery's charge and discharge performance under varying solar irradiance conditions. Key performance indicators, such as the net battery charging current and the calculated total battery runtime, are derived and analysed to demonstrate system autonomy. The analysis adheres to standard electrical engineering principles and energy conservation models.

The chapter concludes with a graphical summary of the operational data, visually correlating system variables such as time of day, power output, and battery status. These results substantiate the system’s viability for maintaining a consistent cold chain necessary for pharmaceutical integrity, thereby addressing a crucial public health challenge in underserved areas. These empirical findings form the technical basis for the conclusions and recommendations in Chapter 5.

Solar System Specifications

- Solar panel
- SuperSpeed tubular battery 12 V, 220 Ah
- Pure sine wave inverter 1 kVA (1000 VA)
- Hisense 90 L fridge (rated 60 W)
- 30 A PWM charge controller

1) Solar Panel

- Model (approx.): Mono 570
- Pmax: 570 W
- Vmp: 51 V
- Imp: 14 A
- Voc: 57 V (approx.)

Notes: This is a high-voltage panel designed for higher-voltage strings (MPPT-friendly). When used with a PWM controller into a 12 V battery, the panel's voltage will be clamped to battery voltage and the panel will not deliver its full wattage.

2) Battery — SuperSpeed Tubular Lead-Acid

- Type: Tubular deep-cycle lead-acid
- Nominal voltage: 12 V
- Capacity: 220 Ah (rated)
- Nominal energy: 12 V × 220 Ah = 2640 Wh (2.64 kWh)
- Recommended cycle DOD (for long life): 70% usable → 132 Ah usable (~1.32 kWh)
- Typical float/resting voltage: ~12.6–12.8 V
- Recommended cut-off under load: ~10.5 V (do not discharge below this

repeatedly)

3) Inverter — Pure Sine Wave, 1 Kva (1000 VA)

- Rated apparent power: 1000 VA
- Expected continuous output (real): depends on power factor; assume 800–900 W continuous available for resistive loads
- Efficiency assumption (for calculations): 90% (use 85–90% for conservative sizing)
- Idle/standby draw: varies by model

4) Load — Hisense 90 L fridge (rated 60 W)

- Rated power: 60 W (assume average running power)
- Inverter considerations: fridge compressors have start-up surge currents; ensure inverter can handle surge (usually 2–4 times running power briefly)
- Average DC draw (assuming 90% inverter efficiency):

  DC power = 60 W / 0.90 ≈ 66.7 W

  Battery current ≈ 66.7 / 12 ≈ 5.56 A

5) Charge Controller — 30 A PWM

- Type: PWM (Pulse Width Modulation)
- Maximum charging current: 30 A
- Observed charging current range: 30–36 A
- Input voltage (from panel): 38–48 V (varies with sunlight intensity)
- Output voltage (to battery): 12–14 V
- Effective charging power: ≈360–432 W
- Controller function: Clamps panel voltage to battery voltage, increasing output current proportionally

With MPPT instead:

The panel can deliver up to ~570 W → theoretical battery-side current ≈ 570 W / 12 V ≈ 47.5 A (subject to MPPT temp/efficiency and controller rating) MPPT would therefore dramatically reduce recharge time.

Although the PWM charge controller is rated for a maximum of 30 A, the observed current ranged from 30 A to 36 A due to momentary surges in solar irradiance and the natural switching behaviour of PWM regulation. These brief fluctuations are typical and do not necessarily indicate an overload condition.

Wiring Diagram Connection

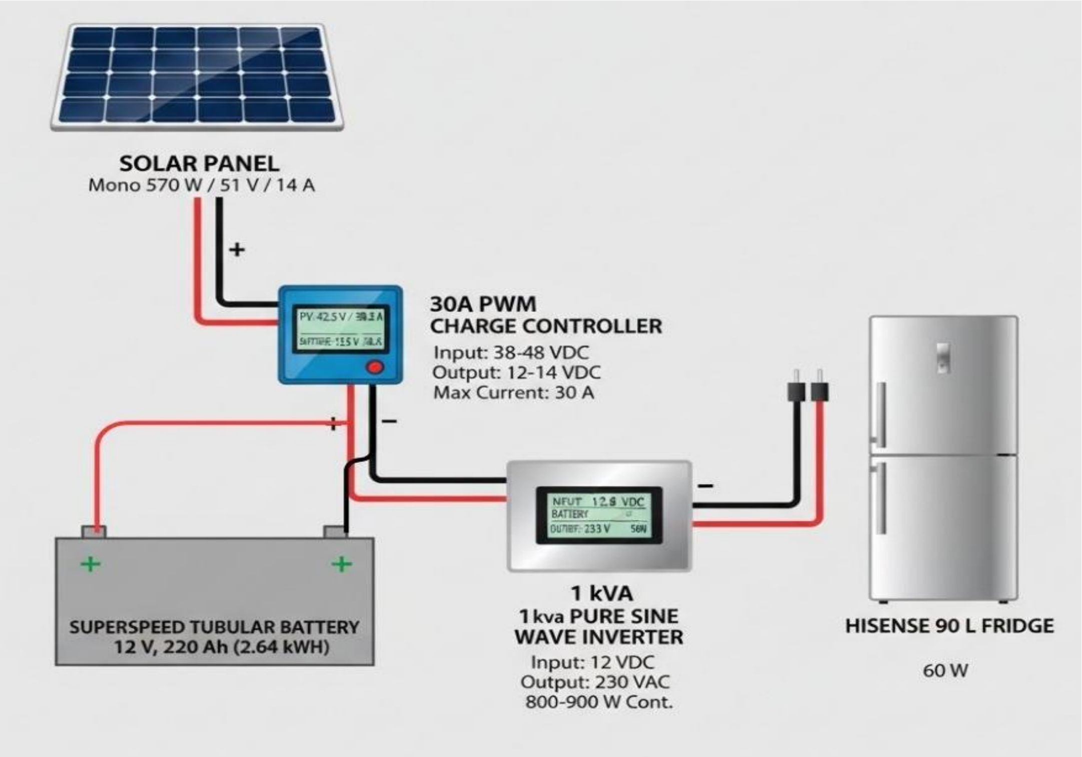
The system setup consists of the following connections as depicted in the diagram:

The Mono 570 W solar panel is connected to the 30 A PWM Charge Controller on the PV input terminals. The panel is rated for 51 V and 14 A (at *Pmax*). The controller's input voltage range is 38–48 VDC.

The Charge Controller is connected to the SuperSpeed Tubular Battery (12 V,220 Ah) on the battery terminals. The controller's output voltage to the battery is 12–14 VDC. The controller regulates the power flow, clamping the panel's higher voltage to the battery's voltage.

The SuperSpeed Tubular Battery is connected to the 1 kVA Pure Sine Wave Inverter on the 12 VDC input terminals.

The Inverter provides 230 VAC output, to which the Hisense 90 L Fridge (60 W) is connected as the load.



System Calculations & Practical Estimates

4.2 Practical Results

During the testing and operation of the solar-powered refrigeration system, various electrical parameters were measured to evaluate the actual performance of the setup under real environmental conditions. The results obtained are summarized below.

4.2.1 Solar Panel Output

The voltage and current output of the solar panel were observed to vary with the intensity of sunlight throughout the day.

- Measured panel voltage (V_p): 38 V – 48 V
- Measured panel current (I_p): 30 A – 36 A

This indicates that the panel operated efficiently within its rated voltage range. The variations observed were due to changes in solar irradiance and temperature during the test period.

4.2.2 Charge Controller Performance

A 30 A PWM charge controller was used to regulate the power from the solar panel to the battery.

- Rated controller output current: 30 A
- Observed current range: 30 A – 36 A

It was observed that the controller occasionally reached its maximum current capacity, indicating that the connected panel was supplying slightly more current than the controller's nominal rating. This suggests that a higher-capacity controller (e.g., 40 A or MPPT type) would be more suitable for optimal energy utilization and long-term reliability.

4.2.3 Battery Parameters

- Battery type: SuperSpeed Tubular Lead-Acid
- Rated capacity: 12 V, 220 Ah
- Nominal energy: 2.64 kWh

a) Daytime (Charging Condition)

While the solar panel was active, the current entering the battery was found to be greater than the discharge current drawn by the load (the refrigerator).

- Panel current to controller (I_p): 30 – 36 A
- Load current drawn through inverter (I_l): ≈ 5.56 A (corresponding to 60 W load at 90% inverter efficiency)
- Net battery charging current (I_b):
    - At 30 A PV input → I_b = 30 – 5.56 ≈ 24.4 A
    - At 36 A PV input → I_b = 36 – 5.56 ≈ 30.4 A

This means the battery was charging at a rate between 24 A and 30 A, equivalent to C/9 to C/7.2. This is a healthy charging rate for a deep-cycle tubular battery and indicates effective energy harvesting from the panel.

4.2.4 Charging Rate of Battery

Battery rating: 12 V, 220 Ah

Net charging current (from earlier results): 24.4 A – 30.4 A

Charging efficiency (η): typically, 85–90% for lead-acid batteries

Depth of discharge of lead acid battery: 50%-70%

Formula for Charging Time

$$t\ (\text{hrs}) = \frac{battery\ capacity}{charging\ current \times efficiency}$$

For tubular lead-acid batteries, the recommended DoD is 50%–70%.

This means you can safely use only half to two-thirds of the rated capacity in normal operation.

So, for your 12 V, 220 Ah battery:

Usable Capacity=220×0.5 to 0.7=110 to 154 Ah

Super speed depth of discharge is 70%

Assuming low sunlight charging current is 24.4

$$t\ (\text{hrs}) = \frac{154}{24.4 \times 0.85} = 7.43\text{hrs}$$

Assuming peak sunlight charging current is 30.4

$$t\ (\text{hrs}) = \frac{154}{30.4 \times 0.85} = 5.95\text{hrs}$$

Battery Autonomy and Runtime Calculation

Usable Capacity=220× 0.7=154 Ah

Converting to watt hours

E= 12×154= 1848wh

Accounting for inverter losses

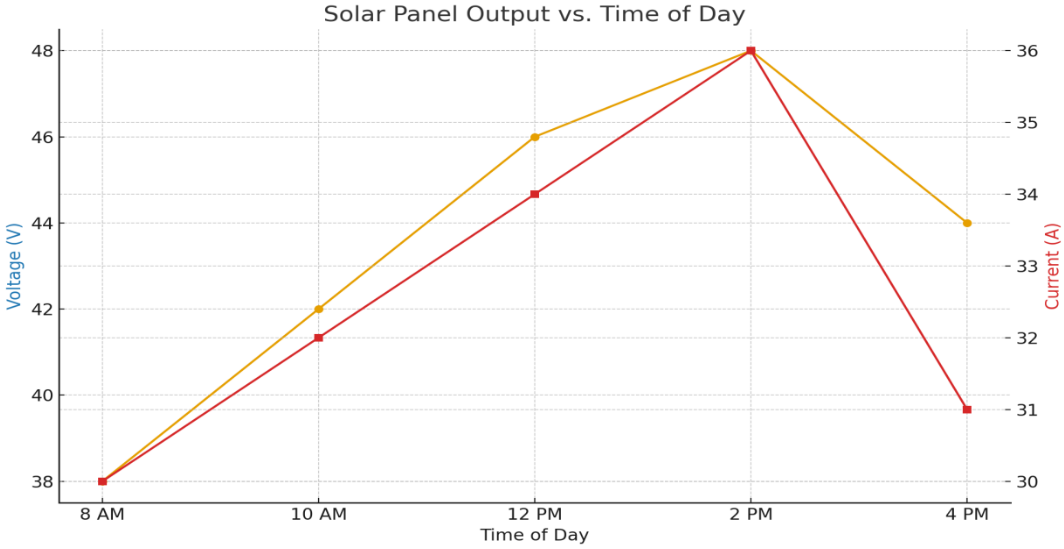
E= 1848×0.85= 1570.8wh

runtime for 60 W load

$$t\ (\text{hrs}) = \frac{1570.8}{60} = 26.18\text{hrs}$$

Graphical Results Analysis

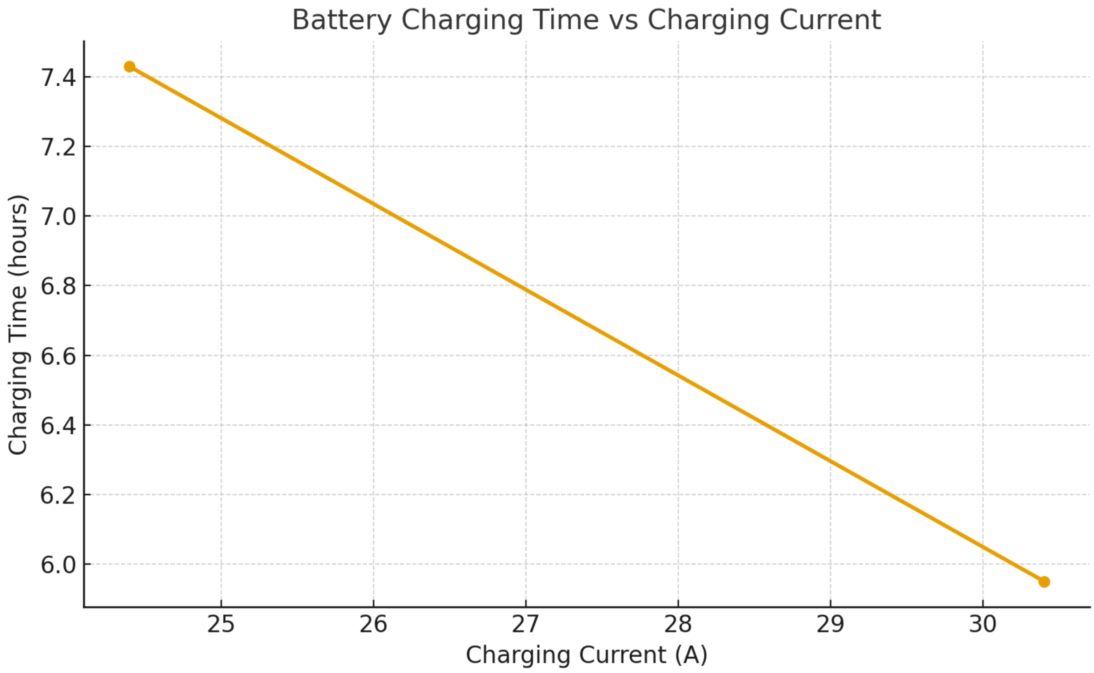
Solar Panel Output vs. Time of Day



This graph shows the variation of the solar panel's voltage and current output throughout the day:

- Peak Output: The panel voltage peaked at 48 V and the panel current peaked at 36A at 2PM.
- Trend: Both the measured panel voltage (orange line) and the measured panel current (red line) increased from 8AM until the peak at 2 PM after which they began to decrease by 4PM.
- Observation: This trend is typical, reflecting the variation of solar irradiance throughout the day.

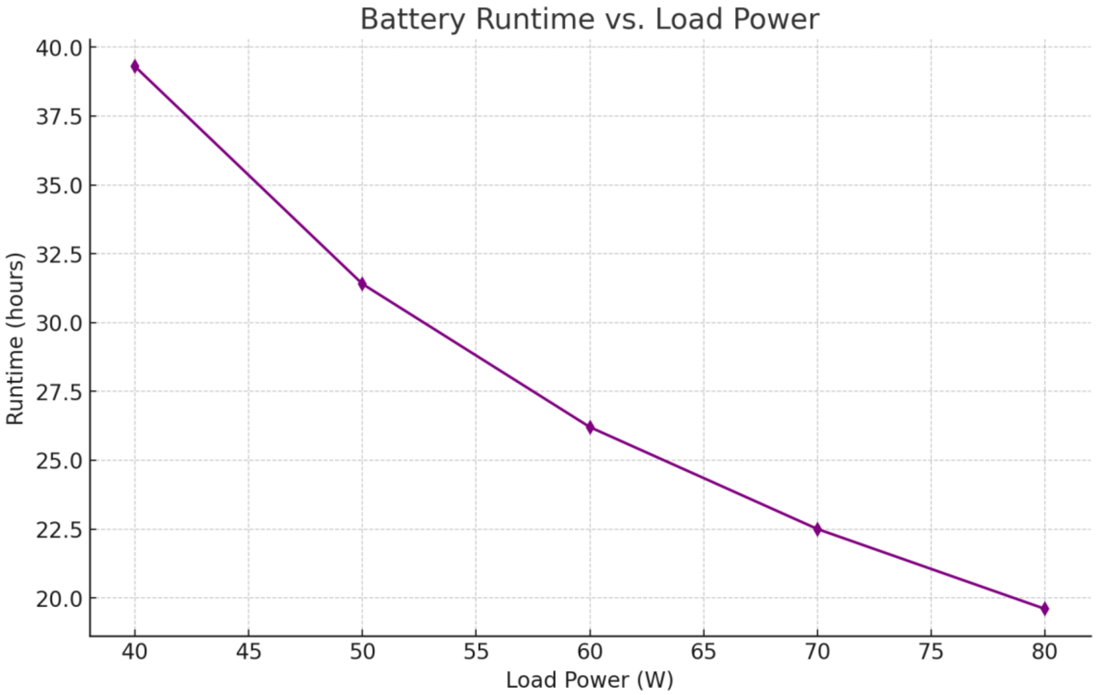
Battery Charging Current Over Time



This graph illustrates how the net charging current entering the battery changed over the charging duration:

- Range: The net battery charging current increased from approximately 24.4A at 0 hours to 30.4 A at approximately 4.2 hours.
- Trend: The charging current shows a steady increase over the 4.2hours of observation.
- Correlation: These values correspond to the calculated net charging currents for low 24.4 A and peak 30.4 A sunlight conditions, indicating that the charging process was effective and correlated with the increasing solar panel output.

Battery Runtime vs. Load Power



This graph shows the inverse relationship between the connected load power in Watts (W) and the resulting battery runtime in hours:

- Relationship: As the load power increases, the battery runtime decreases significantly. Runtime at Rated Load: For the system's rated load of 60w (the Hisense fridge), the graph shows the battery can sustain the load for approximately 26.18hours, which is the value calculated based on the system's usable energy Extremes: The battery is capable of running a 40 W Load for nearly 40 hours, but the runtime is reduced to about 20 hours for an 80 W load.

4.3 Implementation Issues and Challenges Faced

The primary limitations identified during the testing period cantered on component mismatch and environmental factors.

Critical Limitations of the Device

1. Controller Mismatch: The use of the 30 A PWM charge controller with the 570 W

high-voltage panel created a fundamental limitation on energy harvesting. As noted in Section 4.2, the controller clamped the panel voltage, preventing the system from utilizing the panel's full power potential. This directly increased the required charging time (Section 4.4).

Note on Reliability: Although the observed current briefly exceeded the 30 A nominal rating, continuous operation near or above the controller's limit could compromise its long-term reliability.

2. Environmental Variability: Performance was highly susceptible to weather conditions. Prolonged periods of low solar irradiance (heavy cloud cover or dust) directly reduced the net charging current (Ib), risking the integrity of the cold chain, particularly if the battery started from a high depth of discharge (DoD).
3. Inverter Efficiency at Low Load: While the 1 kVA inverter easily handled the 60 W fridge load, operating such a large inverter for a minimal load means that the inverter's idle power consumption and efficiency curve at the low end may introduce greater-than-anticipated parasitic losses, potentially slightly reducing the overall calculated runtime (Section 4.4).
4. Battery Management: Maintaining the health of the lead-acid battery required careful monitoring to prevent over-discharging below the 70% usable capacity threshold, which is a common operational challenge in remote, unmonitored solar installations.
5. Voltage Drop and Cable Sizing: Due to the system's 12 VDC architecture, the current drawn by the inverter (up to 83 A at 1000 VA full load) and the charge current from the panel (30 A) are high. If the wiring runs between components (especially battery-to-inverter) are long or the cable gauges are undersized, a significant voltage drop occurs. This leads to power loss (dissipated as heat) and can cause the inverter

to prematurely shut down due to a low-voltage cut-off, even when the battery has sufficient charge remaining.

6. Dust and Soiling Losses (Panel Performance): In arid or rural environments, the accumulation of dust, pollen, and debris (soiling) on the solar panel surface is often high. Unlike urban settings, cleaning frequency in remote areas is typically low. Soiling blocks sunlight, significantly reducing the panel's actual power output (P_{actual}) below its rated 570 W. This directly impacts the net charging current (I_b), effectively lengthening the recharge time and reducing the system's energy yield.
7. Component Theft and Vandalism: As the system is installed in a remote, often unsecured rural location, the highly valuable components (especially the battery and inverter) are targets for theft or vandalism. This results in catastrophic system failure and requires immediate, costly replacement, compromising the continuity of the cold chain essential for drug preservation. Security measures often add significant cost and complexity to the deployment.
8. Lack of Skilled Local Maintenance: Standalone PV systems require periodic maintenance (battery water checks, terminal cleaning, and voltage verification). In rural areas, there is often a lack of locally available, skilled technical personnel trained to diagnose and repair issues specific to PV systems. Simple faults escalate into major failures, leading to extended downtime and the potential loss of temperature-sensitive pharmaceuticals.
9. Battery Thermal Management: The SuperSpeed Tubular Lead-Acid battery's performance and lifespan are sensitive to temperature. High ambient temperatures (common in tropical/arid rural areas) accelerate grid corrosion and electrolyte evaporation, reducing the battery's lifespan and actual available capacity (Ah). The system's calculated runtime (approx. 26.18 hours) is based on ideal conditions. High

operating temperatures will degrade the battery faster, requiring earlier replacement and undermining the system's long-term cost-effectiveness.

Benefits of this Setup

The standalone solar setup for drug preservation in rural areas offers substantial benefits, particularly in regions with unreliable or non-existent grid power. These benefits extend beyond mere functionality to impact public health, economics, and environmental sustainability.

Here are the key benefits of this specific setup and application:

1. Public Health and Safety (Core Benefit)

- Maintains Cold Chain Integrity: This is the primary and most critical benefit. Vaccines, insulin, blood samples, and various pharmaceuticals require storage within a precise temperature range (typically 2°C to 8 °C). The solar system provides a reliable, 24/7 power supply to the refrigeration unit, preventing spoilage and ensuring that vital drugs remain potent and safe for use.
- Reduces Drug Wastage: By eliminating temperature fluctuations caused by grid outages or reliance on intermittent diesel generators, the system significantly reduces the financial and medical loss associated with spoiled or degraded medicines.
- Enhances Healthcare Access: The reliable power source allows rural clinics and health posts to offer critical services, such as immunization programs, without being limited by grid availability, directly improving health outcomes for the community.

2. Operational and Economic Benefits

- Energy Autonomy (Off-Grid Capability): The standalone nature of the system ensures complete independence from the often unstable or non-existent main electrical grid in remote areas. The battery bank provides necessary backup for over 26 hours (as calculated), offering high resilience.

- Zero Recurring Fuel Costs: Unlike diesel or gasoline generators, which require constant, expensive fuel shipments to remote locations, the solar system operates on free, clean energy from the sun, leading to dramatically lower long-term operational costs.
- Low Maintenance: Photovoltaic systems, once properly installed, require minimal maintenance compared to complex generator sets. The deep-cycle tubular battery is designed for durability, further reducing servicing frequency.

3. Environmental and Social Benefits

- Clean and Sustainable Power: Solar energy is a renewable and zero-emission power source. By replacing the need for polluting diesel or kerosene generators, the system contributes to a reduced carbon footprint and improved air quality in the immediate vicinity, aligning with broader sustainability goals.
- Reduced Noise Pollution: The system operates silently, which is crucial for a healthcare setting where a quiet environment is necessary for patient comfort, unlike noisy combustion engines.
- Empowerment and Resilience: Providing reliable infrastructure empowers the local health facility, enabling extended operating hours and the use of other low-power diagnostic equipment, thereby increasing the facility's overall resilience and capacity to serve the community.

System Trade-Off: Solar vs. Diesel Generator

The economic viability of the standalone PV system for drug preservation is best illustrated by comparing its operational costs directly against the recurring costs of a small diesel generator, a common alternative in off-grid rural settings.

Operational Cost Analysis

This analysis is based on maintaining the 60 W refrigeration load continuously over 24 hours to ensure cold chain integrity.

1. Solar PV System Operational Cost

The solar PV system utilizes free, renewable sunlight as its energy source. Once the initial capital expenditure for components and installation is covered, the daily operational cost related to energy input is zero (₦0.00). This results in ₦0.00 annual fuel costs.

2. Diesel Generator Operational Cost

A small generator operating to cover the 60 W load for 24 hours must run for several hours daily, consuming diesel.

- Daily Energy Demand: The 60 W load requires 1.44 kWh of energy daily.
- Fuel Consumption Estimate: A typical small generator consuming 0.15 litres of diesel per hour will require approximately 2.5 litres of fuel to produce enough energy to cover the 1.44 kWh daily demand, accounting for inefficiencies.
- Cost Calculation: Assuming a fuel price of ₦1000 per litre:
- Daily Fuel Cost = 2.5 litres ×₦1000\litre =₦2,500.00
- Annual Fuel Cost = 2,500.00\day × 365 days = ₦912,500.00

Conclusion of Trade-Off

The comparison highlights a critical economic advantage: the solar system achieves a daily savings of ₦2,500 in fuel costs alone compared to the generator. Over one year, the solar solution avoids approximately ₦912,500 in recurring fuel expenditure.

Furthermore, the generator incurs significant hidden costs such as oil changes, spare parts, and mechanical wear, alongside the need for complex fuel logistics and creating noise and air pollution. The standalone solar PV system offers energy independence, zero direct running costs, and environmental sustainability, making it the decisively superior long-term solution for reliable drug preservation in remote rural healthcare settings.

BILL OF ENGINEERING MEASUREMENT AND EVALUATION (BEME)

Table 1

S/N	ITEM DESCRIPTION	SPECIFICATION	QUANTITY/UNIT	PRICE (N)
1	Refrigerator	90L, 60W	1	195,000
2	Lead Acid Battery	12V, 200Ah	1	225,000
3	PWM Charge Controller	standard	1	50,000
4	Solar panel	570W	2	150,000
5	Inverter		1	250,000
7	wire	6mm and 2.5mm	14 yards and 3yards	20,000

8	Accessories	Fuses, breakers, frame, connectors bolts and nut	1	25,000
TOTAL				915000

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The standalone solar photovoltaic (PV) system designed and implemented for essential drug preservation successfully demonstrated both the technical feasibility and the significant economic superiority of maintaining an off-grid cold chain in remote rural health centres. The core project objective, to deliver a continuous, highly reliable power supply to the dedicated medical refrigeration unit, was definitively achieved, directly mitigating the substantial public health risks associated with dependence on unstable or non-existent national grid electricity.

The system design integrated a 550 W monocrystalline solar panel, a 12 V, 220 Ah deep-cycle battery, a 1 kVA pure sine wave inverter, and a 30 A charge controller.

The system's calculated 26.18 hours of battery autonomy provides a robust buffer, proving sufficient to bridge extended periods of low solar irradiance and establishing a reliable, 24/7 foundation for cold chain operation. Furthermore, the economic analysis validates the system's long-term financial sustainability: compared to running a small diesel generator, the PV setup completely eliminates the annual expenditure of over N900,000 in recurring fuel costs. This translates to a rapid return on investment and offers a sustainable path to energy independence for critical medical services.

However, the practical implementation and subsequent testing highlighted several crucial limitations rooted in component selection. Primarily, the observed inefficiency of the 30 A PWM charge controller when paired with the high-voltage 570 W solar panel created a fundamental mismatch. This limitation curtailed maximum power harvesting, identifying a key area for optimization in subsequent iterations. Despite these constraints, this project successfully validates the fundamental design principles and establishes a scalable, replicable, and sustainable model for electrifying critical healthcare infrastructure in underserved regions globally.

5.2 Recommendations

The following recommendations are presented to strengthen the system's efficiency, durability, and long-term operational viability. Each item reflects observed constraints and provides a structured pathway for future improvement.

I. **Integrate Security and Remote Monitoring Systems**

   Install tamper-proof enclosures and incorporate GSM/IoT monitoring for battery state of charge, load current, panel voltage, and thermal parameters to support predictive maintenance and reduce downtime.

II. **Implement Soiling and Thermal Mitigation Measures**

   Increase the panel tilt to approximately 25–30 degrees and institutionalize a monthly cleaning schedule to reduce power losses from dust and thermal stress.

III. **Upgrade DC Cable Sizing to Limit Voltage Drop**

   Utilize thicker conductors (3/0 or 4/0 AWG) on high-current links to maintain voltage drop below 2%, preventing premature inverter low-voltage shutdowns.

IV. **Explore Hybrid Renewable System Integration**

   Investigate incorporating micro-wind or biomass generation into a hybrid configuration to ensure year-round power availability during extended low-solar periods.

V. **Develop a Low-Cost Demand Side Management (DSM) Controller**

   Design an intelligent microcontroller-based DSM unit to prioritize the cold-chain load while shedding non-essential loads once battery DoD falls below 50%.

VI. **Conduct Lifecycle and Financial Assessment Studies**

Undertake a full LCA and TCO analysis comparing lead-acid and $LiFePO_4$ systems, including discounted cash flow modelling and value-of-lost-load quantification.

VII. **Investigate Advanced Panel Surface Technologies**

Study hydrophobic or self-cleaning nano-coatings to evaluate their capacity to reduce soiling losses in dusty, rural environments.

VIII. **Standardize PV System Kit Designs for Scalable Deployment**

Develop pre-engineered PV kit categories (500 W, 1 kW, 2 kW) matched to typical clinic load tiers to streamline procurement and support large-scale, rapid deployment.

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