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Development of a Direct Current (DC) Domestic Solar Powered Deep Freezer for Home Usage

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Abstract. This article is about the development of a direct current (DC) domestic solar freezer for home usage. Electricity generation and distribution has been the bane of developing countries and Nigeria is not an exception. Nigeria with a population of over 200 million people, the largest in Africa and also the largest producer of oil in Africa, cannot steadily and consistently produce 5,000 MW of electricity daily. A lot of people depend on fossil fuel powered generators for their daily power supply needs. At times, these fossil fuels are either too expensive or not readily available to purchase. These factors had pushed living expenses to the roof. Food is the energy of life. It is what empowers and energizes man to perform his daily activities. Households cannot afford to buy foodstuffs especially perishable ones in bulk to store for later use for lack of reliable electricity supply to preserve them. Nigeria is located in the tropics where sunlight is in abundance. This abundant sunlight can be harnessed to produce electricity. Solar photovoltaic (PV) panels are used to charge batteries and in turn used to power DC deep freezer without an inverter charger system. The DC domestic solar freezer was designed and retrofitted with a DC compressor. It is able to work throughout the day and night by incorporating battery bank for storage. This system will eliminate the environmental pollution from fossil fuel if to be powered by generators, power loss through the inverter and reduced the initial cost of development since inverter is not part of the set up. This solar DC freezer will be saving the environment 173.60 kg of carbon dioxide every year. This is the amount of carbon dioxide that would have been released into the atmosphere if the deep freezer is to be powered with fossil fuel generator.

1. Introduction

Demand for electricity has increased greatly in recent years. This is because of numerous variables like development in economy and population in developing nations, a steady increase in comfort levels in advanced nations, the demand for more products, and the rise in the quantity of electric vehicles for public transportation and private use. The rise in environmental and political problems in relation to the use of fossil fuel are the main setbacks for the utilization of this source of energy. One of the ways to tackle these setbacks and to bridge the gap for the increasing demand for electricity demand all over the world is the utilization of photovoltaic systems which used in conversion of solar energy from sunlight into electricity (Charfi, et al., 2018). A strong commitment to decrease the energy utilization of buildings and the improvement of their negative environmental impacts has made researchers to provide new systems and technologies (Madessa, 2015). Numerous researchers were inspired by this clean technology to investigate the performance of various systems with the goal of maximizing PV production at the lowest possible cost. The level of environmental pollution is rising as a result of the rising demand for electricity. The use of renewable energy would help prevent or mitigate this problem of environmental pollution. Solar photovoltaic (PV) systems are used worldwide for clean electricity production (Charfi, *et. al.*, 2018; Soomar *et al.*, 2022). The photovoltaic (PV) systems that converts the solar energy into electricity are the most common and one of the simplest forms of renewable energy sources. Photovoltaic simulation tool can be used to predict the quantity of energy generated by the solar PV system. 98 GW of new solar PV capacity was added worldwide in 2017, and 402 GW of new PV capacity had been installed by the end of 2017 (Sawin, *et. al*, 2018). The electricity generation by the solar PV panels increases as their efficiency is enhanced. Sunlight is directly converted into electrical energy by solar PV technology (Wu, *et. al*, 2017). Cotfas and Cotfas (2019) reviewed some methods developed previously to improve the performance and the longevity of solar PV panels during operations. The conclusion revealed that improving the energy generation by the solar PV panels are dependent mainly on the geographical location, climatic conditions, and the materials used. Kayode, *et. al.*, (2019) designed and retrofitted a 200 litres solar power freezer refrigeration system that runs on the solar energy. This was undertaken to combat epileptic power supply and the non-existent grid power supply in the rural areas. Salilih *et. al* (2020) studied the impact of evaporator and condenser operating pressures on the effectiveness of a directly connected variable speed solar refrigeration system. Compressor speed, power consumption, refrigerant mass flow rate, and cooling capacity are examples of performance metrics that were taken into consideration. The saturation temperatures were used to express the working pressure of the refrigeration system at the evaporator and condenser. Sensitivity analysis of two cases were carried out in this study. In the first case, it was discovered that every performance parameter that were considered was susceptible to changes in the evaporator's saturation temperature. The other two performance parameters (refrigerant mass flow rate and cooling capacity) showed significant sensitivity to variation in saturation temperature of condenser in the second case, whereas compressor speed and power consumption showed negligible sensitivity. Osaze & Okilo (2020) investigated the construction of solar powered refrigerator. It identified some major parts of solar refrigerator. The freezer is required to have power of 400W and work for ten hours (10hrs). Awan, *et. al*, (2020) observed that these solar PV panels can be mounted on structures on the ground, on the appropriate rooftop or integrated in the building windows and facades and that the solar PV panels should be tilted in order to have maximum solar irradiance during the day. Biswas and Kandasamy (2021) constructed Solar Thermoelectric Cooler (STEC) and investigated the consequences of changing the electric current input on the cold side temperature of TEM, cooling capacity, power consumption and coefficient-of-performance (COP). The results showed that the cold side temperature reduced to $5 \pm 0.2\ ^{0}$C in 120 minutes and 180 minutes without and with product load (0.5 kg fish fillets) respectively. It was concluded that, when there is no access to electricity, the STEC could also be considered an alternative green energy option to the AC domestic refrigerator. Alsagri (2022) discussed several studies proving the influence of different characteristics on a system's overall efficiency. So, literature review of PV-powered cooling cycles research was conducted as a result. PV technologies were thereby classified into three types for ease of identification: PV, PVT, and CPVT. Exergy Studies, Experimental Studies, and Simulation and Numerical Studies are the three main aspects the works were divided. The paper categorized and rated refrigeration-assisted solar systems based on exergy destruction, exergy efficiency, and COP of cooling cycles. The findings revealed that PV panels have the highest exergy destruction in the majority of the systems. It is found that employing PV technologies has a high potential for meeting cooling needs, particularly in hot climates. Furthermore, the findings of the study are expected to help designers scale up photovoltaic-based cooling systems, resulting in more efficient and sustainable designs. Yusof (2022) developed a portable solar battery micro fridge that uses solar energy for chilling, and has enough capacity to keep the load running for required hours. The design includes a solar panel to harvest energy, a battery to store energy, a control panel to regulate the charging and discharging, and safety features (Mariano & Urbanetz, (2022)). Arduino regulator is included as the control planned framework to the temperature sensor, current sensor, and LCD as information and result. For the suitability of a solar system on the mini fridge, two tests were performed: battery charging to PV modules and load testing to the mini fridge. The result indicates that the battery might supply for more than two hours because 14.29% of the battery is still accessible before the supply runs out. After 2 hours, the small fridge maintained a temperature of roughly 16 degrees. It was concluded that the study is significant for the creation of a portable small fridge powered by a solar battery that can last more than two hours for medical personnel usage. Riffat *et al* (2022) presents the development and experimental investigation of a sustainable and affordable domestic refrigerator for rural areas with unreliable grid or no grid connection. The refrigerator utilizes a mini refrigeration unit based on a micro-DC compressor, which can self-adjust its speed to solar PV panels power output variation with the intensity of solar radiation to maximize cooling. The refrigerator is packed with Phase Change Materials (PCMs) during the time of high solar radiation and, after sunset PCM will release its cooling energy to maintain the temperature of fridge to extend the cooling. Gunapriya *et al* (2022) observed that employing solar energy as a renewable source of energy for the DC Refrigeration in rural locations will provide a sustainable and cost-effective option for places with intermittent power supply. As an outcome, they carried out a study to illustrate how rural electrification can be provided at a low cost and with minimal maintenance by using a DC Refrigerator. Silas Stephen *et al* (2022) discussed the effectiveness and affordability of DC loads in residential loads but however, the main disadvantage is non availability of suitable DC appliances in the market. The domestic loads can be run more efficiently and affordably on the DC power system, resulting in net zero energy buildings. It is concluded from the analysis that developing DC appliances for the market will enable savings in energy and costs in homes. Koirala *et al* (2023) aimed to study the Klien-Nishina (KN) cross section on the basis of scattering. Scattering model was developed and materials made up of carbon, tungsten, bismuth, tungsten carbide and bismuth carbide were selected. The study found that bismuth and bismuth carbide material have high KN cross section than other, due high cross section bismuth and its carbide is best for radiation shielding. It was discovered that bismuth and its carbide are considered best than others. Ma *et al* (2023) illustrated the characteristics of low voltage direct current supply and utilization system (LVDCSUS) in order to show its progression and it's possible application and the introduction of the application of LVDCSUS technologies as well as demonstration projects in China. Aside from the development of the LVDCSUS, important technologies, such as planning and design, voltage levels, control strategies, and key equipment of LVDCSUS were also discussed. Future application areas of LVDCSUS were analysed. Almatrafi *et al* (2023) investigated the consequences of variable solar irradiance, Solar Heat Transfer Fluid (SHTF) type, and the Cascaded Refrigeration Cycle (CRC) working fluid on refrigeration capacity and exergy efficiency of combined system. The result indicates the most efficient SHTF with air to follow is helium. Nwokeabia *et al* (2023) carried out ground radiometric and aeromagnetic dataset studies in some parts of Southeastern Nigeria within latitudes 5^{o} 001 N and 6^{o} 301 N and longitudes 7^{o} 001 E and 8^{o} 301 E. it covered an area of about 27,225 km^2. The results showed that the mean concentrations of the radionuclides Uranium (U), Thorium (Th) and Potassium (K) present in the area are 3.02 ppm, 11.22 ppm and 0.43 % respectively. On the average, the absorbed dose rate for the specific area is less than the standard average value of 60n $Gyph^{-1}$. The results from the magnetic study showed that the sediment depth of 2 to 6 km in the area of study. The result showed that the Curie Point Depth inversely varied with heat flow. This means that heat flow reduces as the depth of curie increases. Ajayi, Sobamowo, & Nnadi, (2023) developed thermal models in 2-D for the heat conductions through multilayer walls of a refrigerator for the study of thermal function of a refrigerator that is solar energy powered. They develop a refrigerating system in the tropics where the ambient temperature is higher than in temperate countries where similar imported refrigerating systems are imported from. The performance of these developed refrigerating units was studied. They employed finite difference method to solve the equations developed numerically. The operations of the refrigerating units under various surrounding temperatures were modelled. The system set up, operations and evaluations were carried out successfully. From the simulation results obtained, it can be concluded that the operations and the effectiveness of the refrigerating system unit was dependent on the ambient temperature, convective heat transfer coefficient, thicknesses of the composite walls, the insulating materials, thermal property of the wall component and the insulating material used for the construction of the refrigerator. Chinafreezers.com (2023) noted that basically, the solar DC freezers are the same as the traditional freezers internally and principally. The only difference is the power of the solar DC freezer comes from renewable energy (Solar PV panels). The solar DC freezers do not pollute the environment unlike the traditional freezers running on conventional fuels and polluting the environment. The population in the underserved areas or areas without electricity supply from the national grid are other reasons for solar DC freezers development. They opined that development of solar DC freezers is major innovation in the freezing industry and have large developmental space in the future and will contribute greatly to environmental protection. Amaris *et al* (2023) evaluated and discussed a small-capacity direct-current refrigerator having internal heat exchange using R600a, R290, R717, and R134a as case studies, for independent solar refrigeration. A thermodynamic model to assess a 200 W refrigerator performance at evaporation temperatures of -32/-10 °C was developed, condensation temperatures of 35/46 °C, and internal heat exchanger effectiveness values simultaneously considering the environmental conditions. Results obtained indicated the R290 system coefficient of performance (CoP)) increased by 2.6% higher than R134a. The CoP of R600a system 2.7% higher than R134a, under favorable conditions. The R717 system was higher than compressor discharge temperature limits, which made it unsuitable present application. However, the internal heat exchanger was found to be suitable in reducing exergy destruction in the compressor and expansion valve but increased that in the condenser for R134a, R600a, and R290. Therefore, the effectiveness of the internal heat exchanger recommended should be 0.4 for R600a or 0.3 for R290 at an evaporation temperature of -32 °C. De Decker (2023) noted the possibility of connecting the conventional fridge or freezer to a solar PV panel directly but observed that this appliance will quickly heat up at night when the sun is down. Increasing the insulation thickness from 2.5 cm to 12.5 cm was one of the solutions suggested. This solution will reduce the energy consumption of the appliance by a factor of four (4). Another suggested solution was increasing the passive cooling of the refrigerator by adding water tank to act as storage for thermal mass which can be released when the sun is down thereby extending the cooling. Another suggested solution is to design the fridge to open at the top which reduces heat/energy loss when opening the door since cold air is heavier than the ambient air. All these suggested solutions bring about energy efficiency. Yashwandra *et al.*, (2023) observed that developing countries have a growing interest in refrigeration for food and vaccine preservation and suggested the use of simple refrigeration system powered by solar without grid electricity in rural areas. They also noted that solar radiation is most readily available energy source in areas with a lot of sunshine. They developed the prototype modelling of solar powered refrigerator. The simulation is carried out using the MATLAB tool, and it was determined that the Zeta converter is the ideal module for the hardware prototype model. Their simulation and the hardware results gave satisfactory performance. The objective of this present work is to develop a direct current deep freezer powered by batteries and solar PV panels for domestic use.

2. Materials and Methods

2.1 Materials

2.1.1 Solar Photovoltaic Cells Modules

Photovoltaic cells are devices that convert sunlight energy into direct current (DC) electricity. The sun's photons, when it come in contact with the cells' semiconductor (typically a form of crystalline silicon), and these contacts will free up electrons in the semiconductor. An applied electric field moves the electrons in a particular direction through a circuit, producing direct current (DC) electricity. Solar modules can be wired together in series to form strings during installation, or they can be wired together in parallel to form an array. The maximum power generated is given in **Eqn. 1**

Maximum Power generated, $P_{max} = V_{mp} \times I_{mp}$ **Eqn. 1**

Fill factor: fill factor is the ratio of maximum power and the product of I_{sc} and V_{oc} and it is given in **Eqn. 2:**

Fill factor, FF = $\frac{V_{max} * I_{max}}{V_{oc} * I_{oc}} = \frac{P_{max}}{V_{oc} * I_{oc}}$ **Eqn. 2**

2.1.2 Charge regulators/controllers:

This helps to manage the electricity current flow between the loads, energy storage (backup battery), and solar PV panel arrays. The major aim of the charge controller is to prevent the backup batteries from damage resulting from overcharging or excessive discharge. The internal mechanism of the charge controller operates in the switch-on and switch-off modes. For instance, when a terminal voltage supplied from the solar PV panels to the battery bank increases, and the backup battery charge is above a specific threshold value (V_{max}^{off}), the control switch disengages the PV array. The array is re-connected back whenever the terminal voltage of the backup battery falls below a certain value (V_{min}^{on}). This hysteresis cycle prevents the batteries from overcharging and excessive discharging. The charge controller used for this project is a multipower point tracker (MPPT) type that supports voltage conversion and power tracking.

2.1.3 Batteries:

Back Up Batteries (BUB) are used in many types of PV systems to support and supply power at low or no sun conditions. In addition, BUBs are needed in solar systems to prevent fluctuation from the PV output due to weather fluctuations. BUB capacities are selected in respect to the load. The batteries can be connected in series, in parallel or series and parallel to match higher system capacity. There are various types of BUBs that are available commercially for solar PV applications, which includes: lithium-ion, lead-acid, nickel-cadmium, nickel hydride, etc. One of the major requirements for the batteries to be used as backup for solar systems is that they must be able to withstand deep charging and discharging cycles without much degradation to its internal system. Batteries are categorized by the nominal capacity (Q_{max}), which represents the maximum number of ampere-hour that can be obtained from the battery under standard condition. The efficiency of BUB can be defined as the ratio of the charge extracted during discharge to the amount of charge required to restore that state of charge. Its efficiency depends on State of Charge (SoC), which is the ratio of the present capacity of the battery to the nominal capacity i.e., SoC = Q/Q_{max}. For instance, SoC = 1 when the BUB is fully charged, and SoC = 0 when the BUB is completely discharged. The lifetime is often presented as the amount of charge-discharge cycles the BUB sustained before losing 20% of its original capacity.

2.1.4 Deep Freezer:

Figure 1, is solar DC deep freezer, during test. It is direct current and connected directly to the charge controller. The need for inverter is eliminated thereby reducing the cost and losses due to inverter.

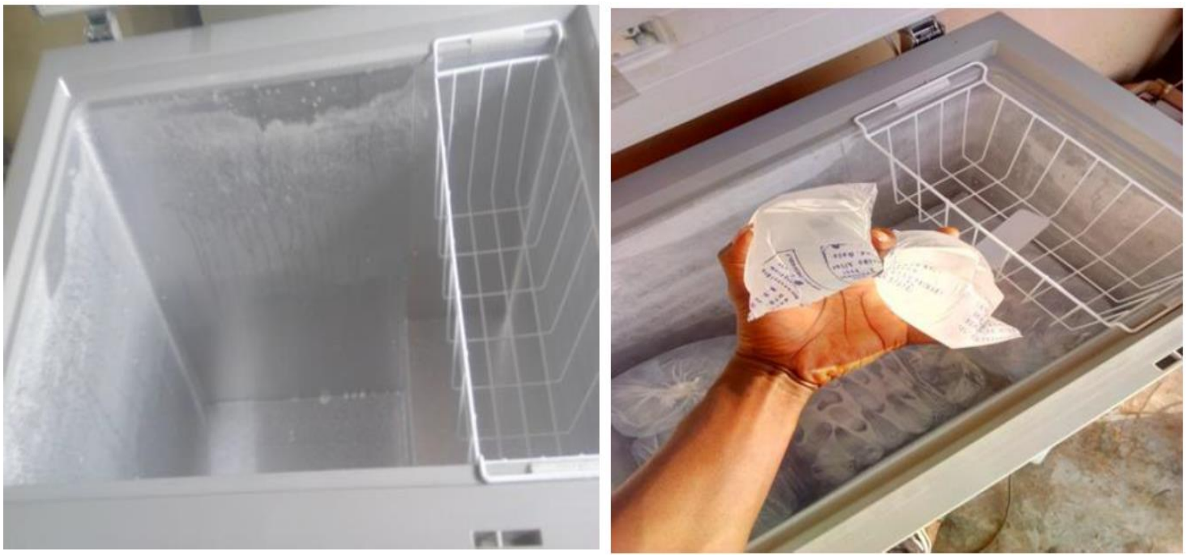

Figure 1: Iced sachet water used for load test

2.1.5 Meteorological data

When determining the performance of a solar PV power system, it is important to take into account the local meteorological data, such as solar irradiation and ambient temperature. Monthly meteorological data for any location can be made available with the help of software. University of Lagos has a meteorological garden where the meteorological data for the school and its locality can be gotten. This data is used to get the monthly average solar irradiation parameter and air temperature.

2.2 Methodology

Here are selected design procedures for the development of a DC deep freezer for domestic use. This design is for the Solar PV panels, back up batteries, etc.

2.2.1 Load Calculation for the Freezer

Cooling load can be calculated as given in **Eqn. 3**

$$Q = mc_p\theta \qquad \textbf{Eqn. 3}$$

where

Q is the cooling load in *kW*

m is the mass of the products to be stored in the freezer in *kg*

C_p is the specific heat capacities of the products to be stored in the freezer in *kJ/Kg K*

θ is the temperature difference between the outside and the inside of the freezer in *K*

A 75 W compressor was selected since this happened to be the smallest compressor available and that was the size removed from the Freezer.

2.2.2 Design analysis and power sizing using 12v/24v DC Compressor deep freezer

The Compressor power required with fan and lighting is 85 W

Freezer power rating = 85 W

Energy consumption per day = 85 W x 24 h = 2040 Wh

2.2.3 Solar panels selection

Power generated/panel = 200 W

Estimated average solar availability per day = 5.2 hours

Energy generated/panel = 200 W x 5.2 h = 1040 Wh

Using 75 % system efficiency = 0.75

The required number of panels is given in **Eqn. 4**

$$\text{Number of panels required} = \frac{\text{Energy consumed}}{\text{Energy generated}} \times \text{Efficiency} \qquad \textbf{Eqn. 4}$$

At 75 % system efficiency, the power output from the = 0.75 x 1040 = 780 Wh

Therefore, number of panels required = 2040/780 = 2.62 panels = 3 Nos of 200 W panels

2.2.4 Back up battery selection

Energy consumption per day = 85 x 24 = 2040 Wh

Battery energy = V x Ah = 12 x 160 = 1920 Wh

Using deep battery 50 % discharge = 0.5

At 50% discharge, Battery output available = 0.5 x 1920 = 960 Wh per battery

Number of batteries required = 2040 Wh/960 Wh = 2.13 = 3 batteries

2.2.5 Charge controller

Solar PV maximum current = 8.09 x 3 = 24.27 A

Margin of safety of 25 % is allowed for the Charge Controller

Maximum working current will be 1.25 x 24.27 = 30.34 A

The charge controller used is a 12/36/24/48 V and 60 A MPPT Auto Charge Controller was used

2.2.6 The Construction of the Deep Freezer

The construction of the solar powered deep freezer started by acquiring a 118 litres conventional domestic freezer body from the scrap market and selection of a DC compressor for use instead of the AC freezer compressor. In actual sense, the 118 litres AC freezer was retrofitted with a DC compressor to turn into DC Deep Freezer. The selected DC compressor was mounted, **Figure 2**., and tightened properly using bolt and nut. The discharge low suction pipe of the compressor is welded to the inlet pipe coils of the condenser mounted on the back of the freezer, dryer is then welded to the outlet of the condenser pipe coils and the capillary tube is joined to the dryer. The capillary tube is also welded to the inlet pipe of the evaporator. The outlet of the evaporator pipe coils is welded back to the return low suction line of the D.C compressor, the compressor is then filled with R134a refrigerant through the charging pipe and closed.

Figure 2: Installation of DC compressor

2.3 Experimental Set-up

The three solar PV panels were connected in parallel (36.7 V) and connected to the Charge Controller. The charge controller is in turn connected to the back-up battery bank and the Freezer. Four number of 12V/160Ah deep cycle batteries were used as the backup battery to power the freezer. 4 mm multi strand cable is used to connect the solar PV panel to the charge controller and battery. The diagram and the real setup are shown in **Figure 3** and **Figure 4**. The solar panels were eventually placed on the roof for maximum exposure to the Sun.

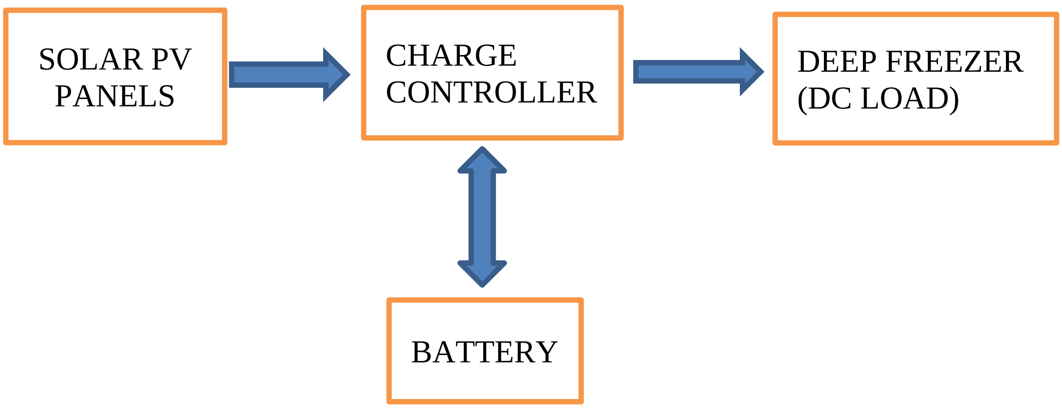

Figure 3: Block Diagram of a complete photovoltaic system without inverter

2.4 Carbon dioxide Savings.

One of the advantages of renewable energy is Carbon dioxide savings, thereby saving the environmental from pollution.

Energy required by the freezer = 0.085 kW x 24 h/d x 365 days/yr

= 744.6 kWh/year

1 kWh of renewable Energy = 0.23314 kg of CO_2 saved

CO2 saved = 744.6 kWh/year x 0.23314 kg of CO_2 saved/kWh

= 173.60 kg of CO_2 saved per year.

Figure 4: Temporal Set-up of Solar panel and DC FREEZER with batteries and charge controller

3. Results and Discussions

The system was tested using 12 Volts and 24 Volts battery output connections. 30 litres of water were used for testing the deep freezer. The water got blocked within a time frame of 10-11 hours when connected to 12 V output and 9 hours when connected to 24V output. It is noted that whenever the voltage drops to 11.5 V from 13.1 V or 23.5 V from 27.4 V full charge, the system automatically shuts down by itself because of the Auto function of charge controller.

The voltage and time of reading is shown in **Figure 5** with load of 30 liters of water. When using 12V/160Ah battery only without panel, the running current tested was 9A with 3A as starting current and 5A at half full load. The voltage was falling throughout the period of observation in **Figure 5** because there was no charging back of the battery bank during the period.

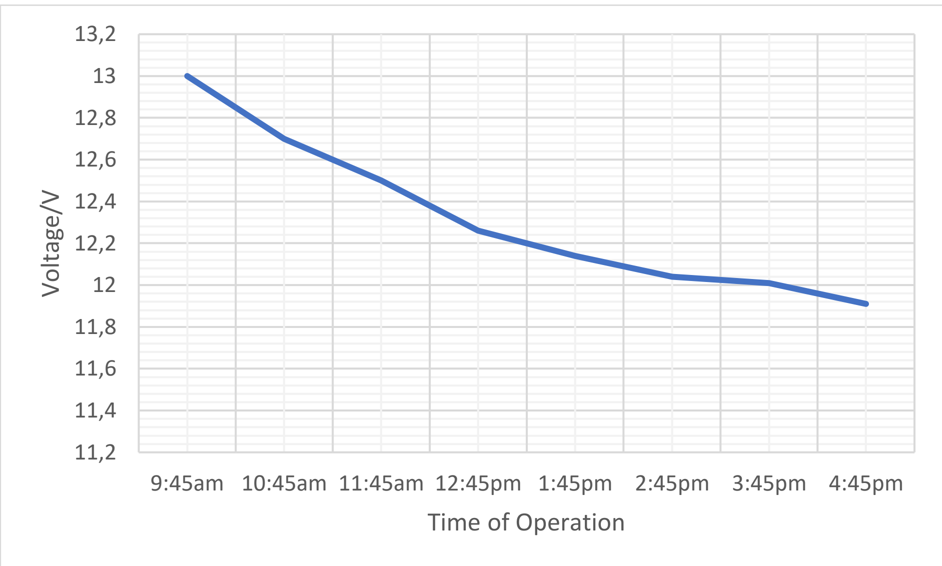

Figure 5: Hourly Voltage Drop at 30 litres of water Load Without PV (160Ah Battery only).

Figure 6 is the test, using 320 Ah batteries with the solar panel (600 W) connected to the battery gave readings of 13.2V on the battery when the load was applied and running current of the device as 5A with 30 litres of load.

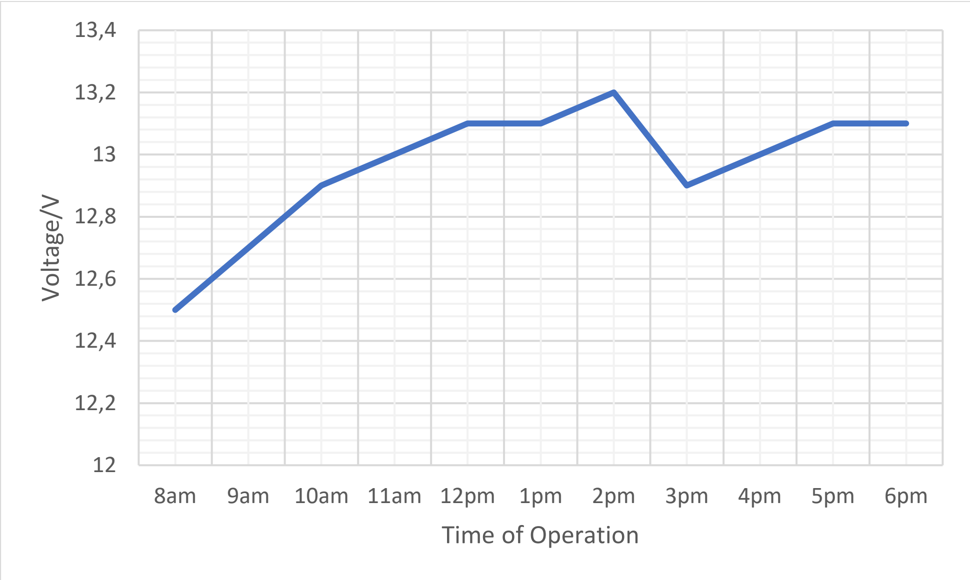

Figure 6: Hourly Voltage Readings at 40litres of water Load With PV (300Ah Battery and 400W Panel).

The voltage kept rising as observed in **Figure 6** due to charge back of the battery bank with solar PV panels. Although there was a decrease in the Voltage around 3 pm this was due to climatic fluctuation of the solar irradiance. **Figure 7** is shown a graph of voltage and time of reading when parallel connection was made using 2 x 12V/160Ah battery.

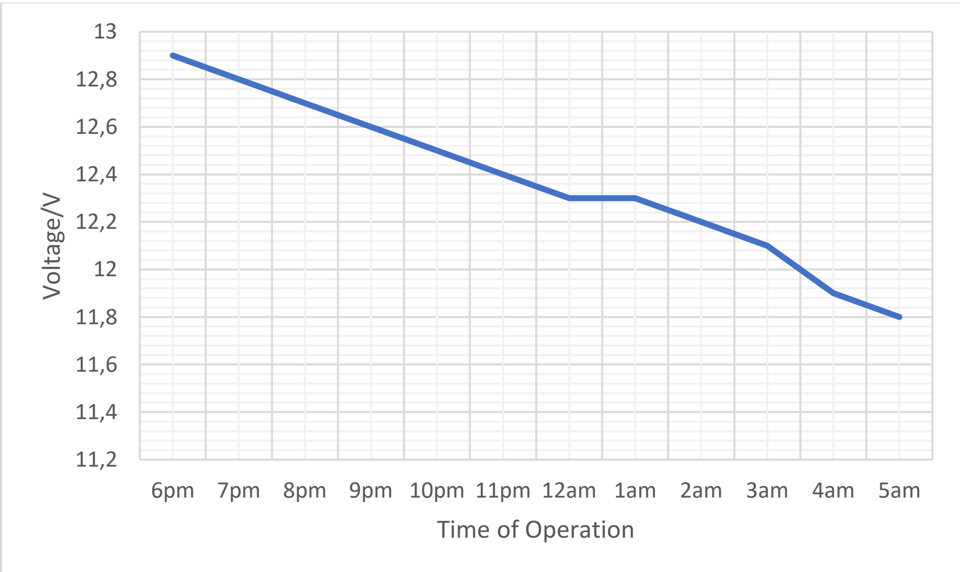

Figure 7: Hourly Voltage Drop At 30 litres of water Load Without PV (For 320Ah Battery only).

The voltage was falling throughout the period of observation in **Figure 7** because there was no charging back of the battery bank during the period due to no sun irradiance although solar PV panels were connected to the batteries. **Figure 8** is the graph of voltage and time of readings when a parallel and a series connections were made using 2 x 2 x 12V/160 Ah batteries with charging support from 3 x 200W solar panels.

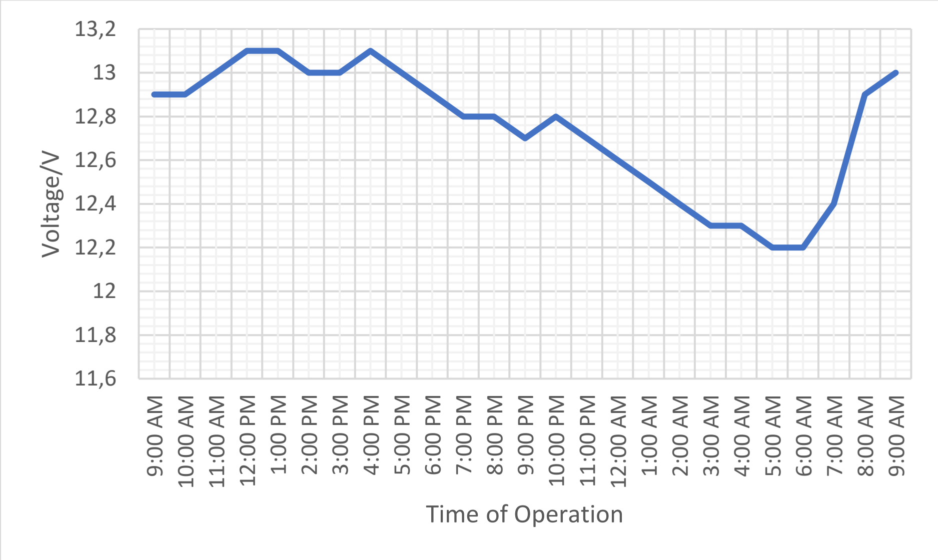

Figure 8: Hourly Voltage Readings At 30 Litres of water Load With PV (For 480 Ah Battery and 600 Watt Panels).

The voltage kept rising as observed in **Figure 8** due to charge back of the battery bank with solar PV panels up until 3 pm when it started to fall steadily through the night until about 7 am when it started to rise again when there is solar irradiance. Although there was a decrease in the Voltage between 1 – 3 pm this was due to climatic fluctuation of the solar irradiance. It was also observed that the freezer did not go off. When there is insolation the following morning, the solar PV panels started charging the backup batteries back. This repeated the cycle with slight fluctuations due to weather fluctuations.

4. Conclusion

A direct current (DC) domestic solar powered deep freezer for home usage was developed and tested. The installed system was able to run effectively and successfully without an inverter and hence reduced both the power losses and cost that would have been associated with the use of inverter, if it was used. Although, the initial cost of production is high due to the cost of solar PV panels and the batteries, but these costs will eventually be recovered with savings on recurrent energy bill. This solar powered solar deep freezer project demonstrated that solar system is a viable alternative energy source for cooling and refrigeration in the tropical climate. Systems such as this can be used suitably in rural areas especially where there is no grid connection. The yearly carbon dioxide saved will be 173.60 kg, which is good for the environment.

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