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Design and Development of a Photovoltaic-Powered DC Vapour Compression Refrigerator with an Incorporated Solar Tracking System

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ABSTRACT: In this work, the design and development of a photovoltaic-powered dc vapour compression refrigeration system for developing countries such as Nigeria is presented. The effects of the variations of compressor speeds on the performance of the refrigerator were investigated. From the field performance test results of the system, at the compressor speeds of 2000, 2500, 3000 and 3500 rpm, the cooling rates were found to be 0.231, 0.485, 0.667 and 0.800^{o}C/min, respectively. Also, it was found that the PV- DC refrigerator achieved the same results at the compressor speed of 3500 rpm as ac refrigerator of the same size connected to electricity from the national grid. There was a significant improvement in the performance of the refrigerator with the use of a solar tracker. The system was tested in a region in Nigeria with an atmospheric temperature range of 25-33^{o}C and lowest solar insolation range 4000-4500 Wh/m^2. This therefore shows that its applicability to different climatic regions in Africa is quite enormous and it could be used for perishable food storage, improvement in the health services and living conditions in remote and rural areas that are unable to access electricity from the grid.

Keywords: Photovoltaic; DC Vapour compression refrigerator; Solar tracker; Design and development; Nigeria.

1 INTRODUCTION

Nigeria has not been able to provide enough electric power for her over 150 million people. The continuous efforts by the federal government to generate 6000MW power to meet energy needs have been proven abortive.

The master gas plan which is meant to produce gas for several existing and planned power stations will take over 3 years to be completed. Meanwhile it is all at the mercy of Niger Delta militants. Only about 40% of the populations have access to erratic electricity supply from the National Grid; out of which, Urban centres have more than 80% accessibility while rural areas, which constitute about 70% of the total population have less than 20% of accessibility to electricity. Moreover, the available 3000MW of electricity generated by PHCN (Power Holding Company of Nigeria) with erratic power supplies has led to generating more than 50% of our energy/electricity from fossil fuel of which the end users has little or no control. An August 5, 2001 British Petroleum report indicates that the 22 billion barrels Nigeria Oil reserves would be exhausted in 29 years if the then production level was maintained [1]. More than 2% annual decline was recorded from 2002-2007. According to the report of Energy officials for Africa's largest oil producer, it was stated that Nigeria's oil reserves (which increased to 32.93 billion barrels, 2008) could dry up in the next 50 years if the then production level was maintained. The research outcome was buttressed in November 4, 2010 [2] as shown in Fig. 1. With all these problems in place, growing population and energy demands, the threats on health and environment accompanying the utilization of fossil fuels to meet the increasing energy is persistently on the high side. The strategies for attaining balance between demand and effects in the country has provoked vast majority in considering the alternative sources.

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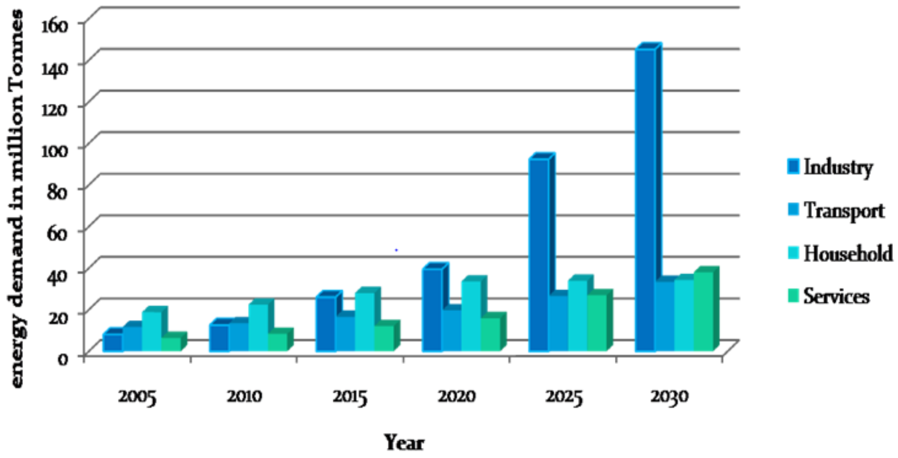

Figure 1: Projection of energy demands by different sectors in Nigeria [2]

Furthermore, as the global challenges, the convergence of rapidly rising costs, dwindling and threatened supply, environmental threats, exploding demand, and growing concern of global climate change are fuelling renewed efforts to find viable energy alternatives. Some of the proposed alternatives such as large scale use of bio-fuels may not be achievable or sustainable-or, eventually practical. Some other interesting possibilities such as geothermal energy may be viable but are local and limited. Solar energy that is virtually an inexhaustible natural source produces little or no greenhouse gases. It is known as a clean and environmental friendly energy source.

Aside from the indisputable advantages of solar energy mentioned above, the consideration of harnessing solar energy among all other alternative sources of energy sources to meet the needs especially in developing countries is based on well established visibility studies. Firstly, most of the countries called developing, like Nigeria, are in or adjacent to the tropics and have good solar radiation available. Secondly, energy is a critical need of these countries but they do not have widely distributed readily available supplies of conventional energy resources. Thirdly, most of the developing countries are characterized by arid climates, dispersed and inaccessible populations and a lack of investment capital and are thus faced with practically insuperable obstacles to the provision of energy by conventional means, for example, by electrification. In contrast to this, solar energy is readily available and is already distributed to the potential users. Fourthly, because of the diffuse nature of solar energy the developments all over the world have been in smaller units which fit well into the pattern of rural economics.

One of the most important applications of this energy source is in refrigerating systems used in daily life. In most urban areas in Nigeria, it is difficult to use refrigerator due to long-term power outages; goods stored in refrigerator such as meat, dairy products, medicine and vaccines are mostly spoilt Moreover, residential areas away from electricity grid in rural areas, similar problems can be experienced frequently. Owing to these persistence problems and the solar insolation potentials (Fig. 2) in Nigeria, we therefore designed and developed a Photovoltaic-Powered DC Refrigerator System. A dry cell battery was built into the system to store charges and run the system at night or when there is no solar insolation and no supply of electricity. Due to the variation in the insolation received by a particular surface with respect to time, a solar tracking system was incorporated.

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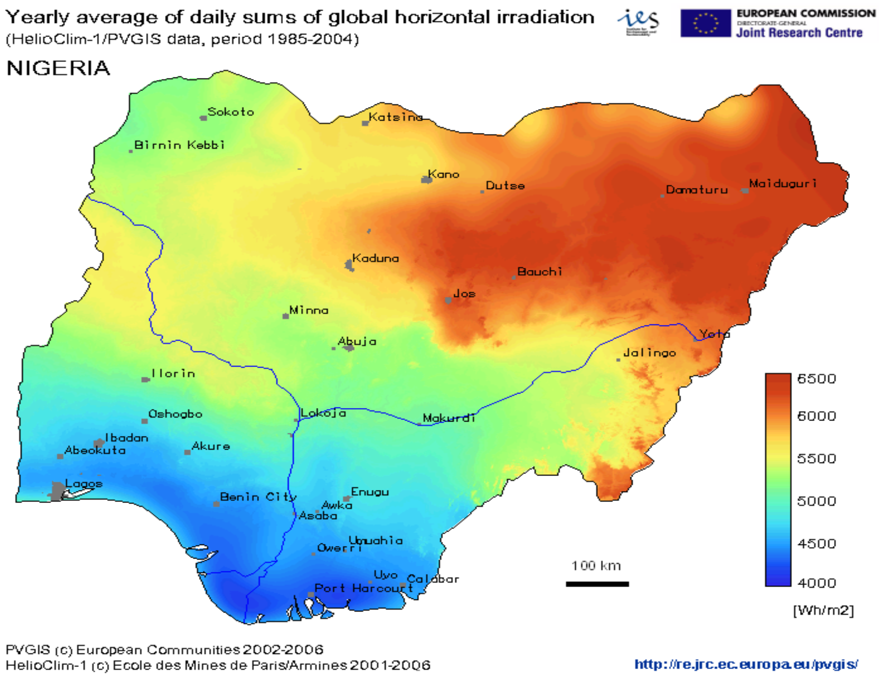

Figure 2: Solar insolation in different States in Nigeria [3]

Various workers have presented different types of solar refrigerators for various applications. Ewert et al. [4] carried out experimental evaluation of a solar PV Refrigerator with Thermoelectric, Stirling and vapour compressor heat pumps. Mohamed and Samuel [5] presented a design, fabrication and economic evaluation of solar photovoltaic (SPV) powered vapour compression refrigeration system to attain favourable conditions for potato storage under different operating conditions. Aktacir [6] presented an experimental study of a multi-purpose PV-refrigerator system. Kim and Ferreira [7] presented an overview of the state of the art of the different solar refrigeration technologies focussing on the potential of these different technologies in delivering competitive sustainable solutions. After critical review of literatures, it was submitted that the most preferred solar system in the refrigerator is photovoltaic system applications [4, 7, 8].

Photovoltaic (PV) is a technology that converts sunlight directly into electricity. With the global demand to reduce carbon dioxide emissions, PV technology is gaining popularity as a mainstream form of electricity generation. A Photovoltaic-powered refrigerator is a cooling appliance that is operated completely with energy harnessed from the sun that has been converted to electricity through photovoltaics (PV). It can store food, medications, and other products that require cold temperatures. Today, due to decrease in the cost of PV panels with the increasing PV panel demand, and in parallel to this situation, increase in duration of use (lifetime) of PV panels, use of these systems has been increasing. However, solar energy is geographically distributed (as for the case of Nigeria is shown in Fig. 2) and highly dependent on the location, changing weather and climate conditions, which makes their direct control extremely challenging and requires storage units as an additional concern [9]. The performance of the PV panels could be increase by incorporation of solar tracker.

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Table 1: Solar energy and surface meteorology over a period of 22 years (July 1983 to June 2005) for Lagos, Nigeria.

Variable	**J**	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**S**	**O**	**N**	**D**
Insolation (kWh/m²/day)	5.59	5.91	5.72	5.36	4.86	4.12	4.04	4.06	4.17	4.58	5.02	5.40
Clearness, 0 – 1	0.60	0.60	0.55	0.52	0.48	0.42	0.41	0.40	0.41	0.46	0.53	0.60
Temperature (°C)	26.21	26.59	26.53	26.56	26.51	25.73	24.80	24.46	24.85	25.23	25.68	25.98
Wind speed (m/s)	4.15	4.30	4.01	3.49	3.00	3.12	3.70	3.87	3.50	2.83	3.05	3.65
Precipitation (mm)	25	36	83	145	233	390	276	128	184	154	53	15
Wet days (d)	1.4	2.8	6.7	9.4	12.5	16.2	13.4	11.8	13.0	11.6	5.0	1.9

Source: NASA Langley Research Center Atmospheric Science Data Center [10]

2 THEORY OF THE PHOTOVOLTAIC- POWERD DC REFRIGERATOR

The Solar Panel is a semiconductor device that can convert solar energy into DC electricity through the “Photovoltaic Effect” (Conversion of solar light energy into electrical energy). When light shines on the solar panel, some of it is reflected, some is absorbed; or some of it passes right through. But only the absorbed light is converted by the solar cells in the panel to generate electricity. The electricity generated through the “Photovoltaic Effect” is in turn used to power a DC Refrigerator (Fig. 3). This type of Refrigerator performs better than the convectional AC Refrigerator because the power loss during the conversion of generated DC electricity by the Solar panel to AC electricity by the use of inverter is eliminated. Fig. 3 shows the set-up of the solar refrigerator system. Due to the variation in solar insolation received by a particular surface with respect to time, the solar panels were mounted on a frame with an incorporated gear-electric motor (12V, 20 Nm) synchronization tracking system which was designed to track the sun’s movement so as to receive maximum insolation at any given time. As the system is particularly based on DC, there is no need of inverter and also a 12V 200Ah deep cycle battery was incorporated into the system store power and run it in the absent of solar power. In order to investigate the performance of the system under different compressor rotational speed, a variable rotational speed DC compressor with a rotational speed ranging from 2000-3500 rpm was used. A light emitting diode was also incorporated into the system to detect faults (whether with the compressor, electronic unit, refrigerant or whatever component), by blinking at a certain frequency corresponding to an error type.

It is shown that as light from the shines on the solar panel, it converts some portion of the light energy to generate electricity through its solar cells. The generated electricity flows through the connected cables to the 12V, 20A charge controller, the part of the refrigerator system that serves as the hub for all the cable lines, keeps the battery in full charge condition, prevents the battery from over-charging and over-discharging and prevents the backflow of current from battery to solar panels especially at nights. So, some portion of the electricity that is being generated by the Photovoltaic is used to charge the battery and the rest are used to directly run the refrigerator.

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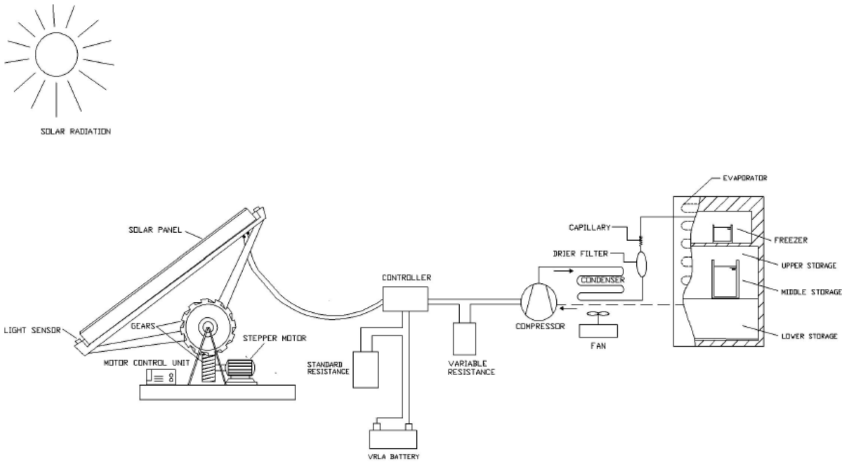

Figure 3: Schematic diagram of the Photovoltaic-Powered DC Refrigerator with incorporated Solar Tracker.

3 THE DESIGN PROCEDURES AND PARAMETERS

The development of the Photovoltaic-Powered refrigerator involved designing, selecting and procuring the components of the refrigerator, construction of the refrigerator according to design, sizing the solar PV modules that will power the refrigerator, designing the solar tracking mechanism and finally incorporating the micro-controller into the tracking mechanism to track the dynamic trajectory of the sun for optimal power generation.

3.1 Sizing of the battery

Since the design of the system to run for 24 hours per day, a deep cycle battery was used to store electrical power during the day so as to run the system at night and when there is no solar power. The sizing of the battery was done as follows.
Total number of hours per day for which the refrigeration system runs on battery only= 7 hrs
Current drawn by compressor = 6.5A

Days of autonomy are the days we receive insufficient photons from the sun; perhaps due to unfavorable weather conditions of rain, cloud and also during winter.
The following parameters were used to design the system:
For this design, we assumed 2 days
Nominal battery voltage could either be 12V or 24V but here, we will make use of 12V battery.
Hence, the required battery capacity is given as:

Total Amp-Hrs required = 7 x 6.5 x 2 = 91Ah

Allowable battery DOD (depth of discharge) = 50%
Battery capacity= total amp-hrs ÷ allowable DOD
= 91÷ 0.50 = 182Ah
Therefore, 12V 200Ah deep cycle battery was chosen for this work being the battery with a capacity nearest to the computed capacity among the standard battery sizes.

3.2 Number of panel required to charge the battery

Average number of sunshine hours per day = 5hrs
Amp-Hrs required to fill up a 200A-h battery after 50% DOD = 100A-h
Required charging current = 100 ÷5 = 20 A
No. of panels required for panels rated at 8.5A
= 20 ÷ 8.5 ≈ 2

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Table 2: Design parameters and Specifications

Evaporating temperature	0°C
Condensing temperature	54°C
Compressor efficiency	85%
Actual suction gas temperature	15°C
Ambient temperature	32° C
Liquid temperature and suction gas temperature	10° C
Danfoss variable speed D.C Compressor	model BD50F
Deep cycle battery	12V 200Ah
Solar charge controller	12V 20A system
Refrigerant used	R134a (CH_2FCF_3, 1, 1, 1, 2-tetrafluoroethane)

Table 3: Panel module specification

PV-module	UE12MF5N
Cell Type	Polycrystalline silicon, 150mm^2
Dimensions	1500x665x46mm
Weight	13.5kg
Maximum Power	125W
Maximum Power Current (I_{mp})	7.32A
Maximum Power Voltage (V_{mp})	17.3V
Maximum System Voltage	DC 600V
Module efficiency	12.6%
Quantity	2

4 EXPERIMENTAL SET UP

After the development of the system, a series of tests were conducted on it to evaluate its performance. The tests were conducted in Lagos state of Nigeria where we have one of the least solar insolation in the Western Africa and in the month of July when the solar insolation 4.04 kWh/m^2 which is the least solar insolation in the state throughout the year as shown in Table 1. To test for the performance of the refrigerator, a variable rotational speed compressor was used, the rotational speed of the compressor was varied from 2000-3500 rpm by varying the resistance across the circuit was using a potentiometer (variable resistor). The results of the experiment were plotted in the following sections.

Figure 4: The Photovoltaic-Powered Vapour compression Refrigerator for Experimental Investigation.

5 RESULTS AND DISCUSSION

From the reading obtained for various compressor speeds, several plots were made showing the relationship between temperature and time. In Fig. 5 shows the temperature variation with time for different compressor rotational speeds of 2000, 2500, 3000 and 3500 rpm. At compressor Speed of 2000 rpm, the refrigerator was switched on at a time when the temperature of the products inside was 30^oC, there was a gradual drop in the temperature as time went on. It took the water 130mins to form ice at temperature of 0^oC corresponding to a cooling rate of 0.231^0C/min. At Compressor Speed of 2500rpm, there is corresponding increase in the cooling rate from 0.231^0C/min to 0.485^0C/min. At the speed of 3000 rpm, the cooling rate increased to 0.667^0C/min. At maximum compressor speed of 3500 rpm, the rate of cooling increased to 0.800^0C/min. At this speed, the power demands of the compressor shoots up to over 70W and so if there is no sufficient insolation at that moment, the load demands switches to battery power, which if not sufficiently charged results into

tripping off of the compressor. This is referred to as overloading of the compressor. However, the temperature of the compressor rises as its speed increases and might get higher than the ambient temperature; hence a fan was incorporated to cool the compressor and electronic unit.

Fig. 6 shows the comparison of temperature variation with time for the various DC compressor speeds and AC compressor connected to National Grid It was observed that the rate of cooling for the domestic A.C refrigerator was approximately the same to that obtainable at maximum compressor speed of 3500 rpm for the D.C compressor refrigerator. It can therefore be gathered that for this model to imitate or achieve results similar to the normal Household refrigerator using A.C compressor connected to National Grid, it must be operated at its maximum speed of 3500 rpm. Fig. 7 depicts the cooling rate as against compressor speeds of the DC refrigerator. As shown in the figure cooling rate of the product increases with compressor speeds. This is because as the speed of the compressor increases, the compressor was doing more work on the refrigerant and increase its cooling capacity thereby increases the cooling rate of the product in the refrigerator system.

Fig. 8 shows the payback period of the Photovoltaic-Powered DC Refrigerator System. From the figure, the payback period for the refrigerator is 17 years i.e. initial investment would have been recovered after 17 years of using the system. The life span of the Solar panel has been found to be 25-30 years, this implies that the system will be used for the next 8-13 years without incurring any cost since the energy from the sun is practically free and

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only battery and the maintenance cost on Solar tracker which is very small amount will be paid for the years. The recovery/payback period for this investment can be very short depending on how much electricity your household uses.

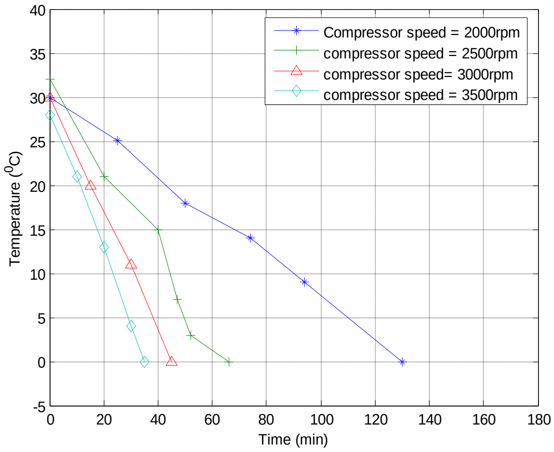

Figure 5: Temperature variation with time for the various compressor speeds

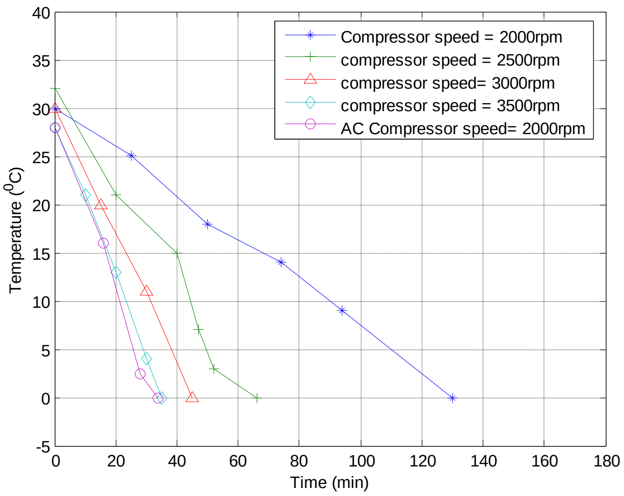

Figure 6: Comparison of temperature variation with time for the solar refrigerator at various DC compressor rotational speeds and Household refrigerator of the same size using AC compressor connected to National Grid

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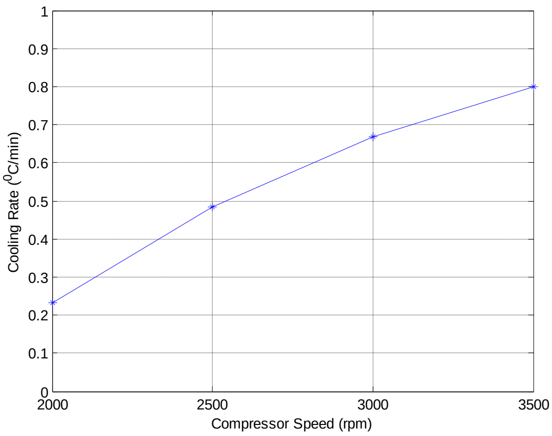

Figure 7: Cooling rate as against compressor speeds of the DC Refrigerator

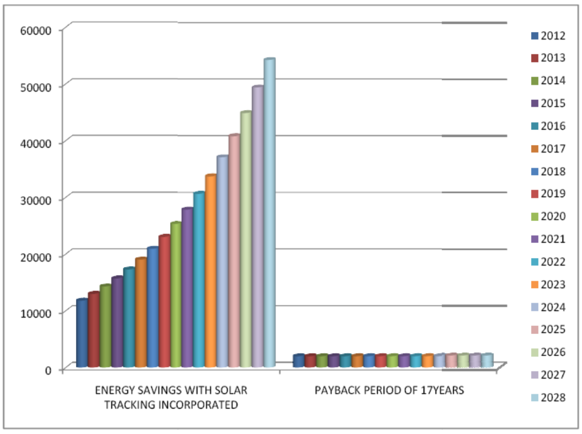

Figure 8: Payback period of the Solar Refrigerator

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6. CONCLUSION

In this work, a Photovoltaic-Powered DC refrigerator was designed and developed in meeting the needs of most rural areas which have no access to national grid and some Africa countries especially Nigeria with unstable and erratic supplies of electricity. Due to the seasonal and daily variation of solar insolation, a solar tracking system was incorporated into the system. A significant improvement in the performance of the Solar panel and consequently of that the refrigerator were recorded. The testing of Refrigeration system in a State in Nigeria with an atmospheric temperature range of 25-33^oC and lowest solar insolation range 4000-4500 Wh/m^2 shows the range of applicability to different climatic regions in Africa is quite enormous and it could be used for perishable food storage, improvement in the health services and living conditions in remote and rural areas that are unable to access electricity from the grid.

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