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Development and Cooling Operation Modeling of a Solar-Powered Refrigerator System with an Incorporated Solar Tracker

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ABSTRACT

The ever-increasing energy demands, rising costs, and alarming depletion of fossil fuels, combined with the environmental risks associated with their use for energy generation, have been driving forces behind the use of renewable energy sources such as solar energy. The conversion and utilization of solar energy as an alternative source of energy, has increasingly aroused the interest of many researchers. In meeting the needs of some Africa countries, especially Nigeria, with unstable and erratic supplies of electricity, a solar-powered refrigerator using electricity from the national grid and the power generated by photovoltaic was designed, developed, and then modelled. The system works on power from the grid system when there is supply of electricity and automatically switches to be powered by the PV whenever there is power failure from the grid system. Moreover, a dry cell battery was built into the system to store charges and run the system at night or when there are no solar insolation and 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. From the field performance test results, the cooling rates of the system when being powered by PV and AC are approximately 0.4°C/min. Therefore, there was a significant improvement recorded in the avoidance of the spoilage of perishable products as compared to when the system was only being powered by the erratic electricity supplies from the grid system. The applicability of the system to different climatic regions in most Africa countries is quite enormous and as it could be used for perishable food storage, it will also contribute to improvement in the health services and living conditions in most regions in Africa countries where there are irregular supplies of electricity from the grid. Since the system requires very little routine maintenance, it is essentially beneficial in developing countries where maintenance facilities are usually poor.

Keywords: Solar energy, dual- powered refrigerator, Solar tracker, Design and development.

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1. INTRODUCTION

The climatic profile, socio-economic development, and energy supply infrastructures in Nigeria indicate a high demand for cooling applications and strongly suggest the use of renewable energy powered systems. Nigeria, with a population of over 150 million people, only about 40% of the population have access to erratic electricity supply from the National Grid; out of which, Urban centers 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 rural areas, with the much greater proportion of the population, come off very poorly in the availability of fossil fuel and electrical energy resources. Thus, the energy types required to run the vapour-compression refrigerators are either not available, -particularly in the remote areas where they are badly needed, or are costly. It also implies that the stated refrigeration technologies, which depend on these energy sources, are not appropriate for the regions. 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. 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 environmentally friendly energy source.

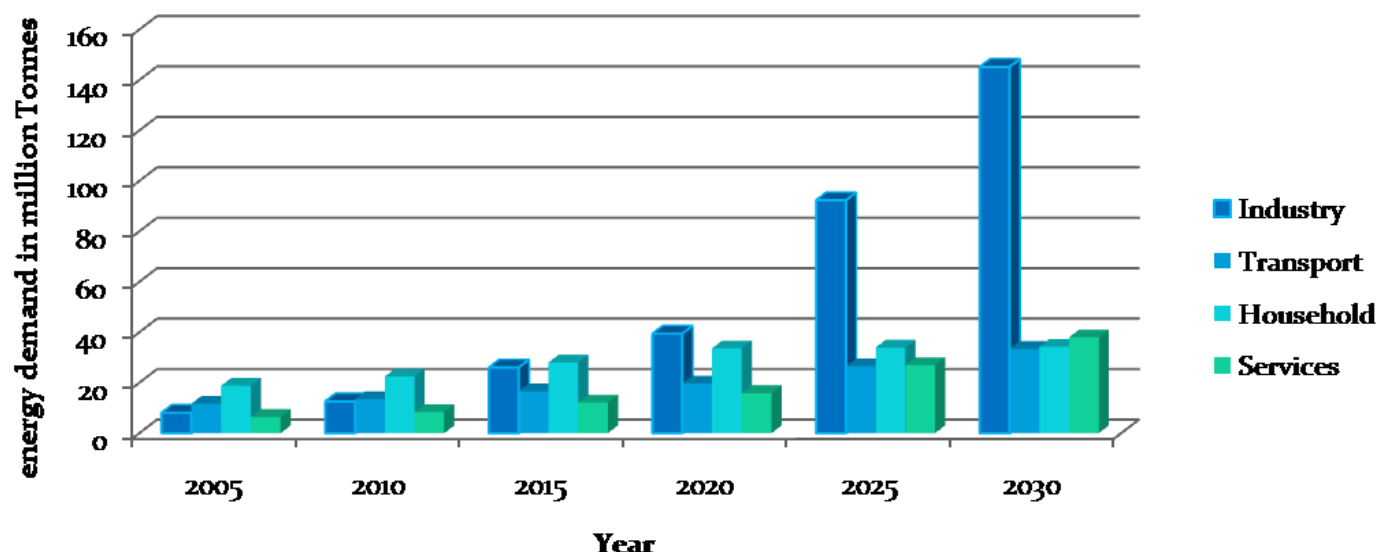


Figure 1. Projection of Energy Demands by Different Sectors in Nigeria. Source: Guardian Newspaper, November 4, 2010.

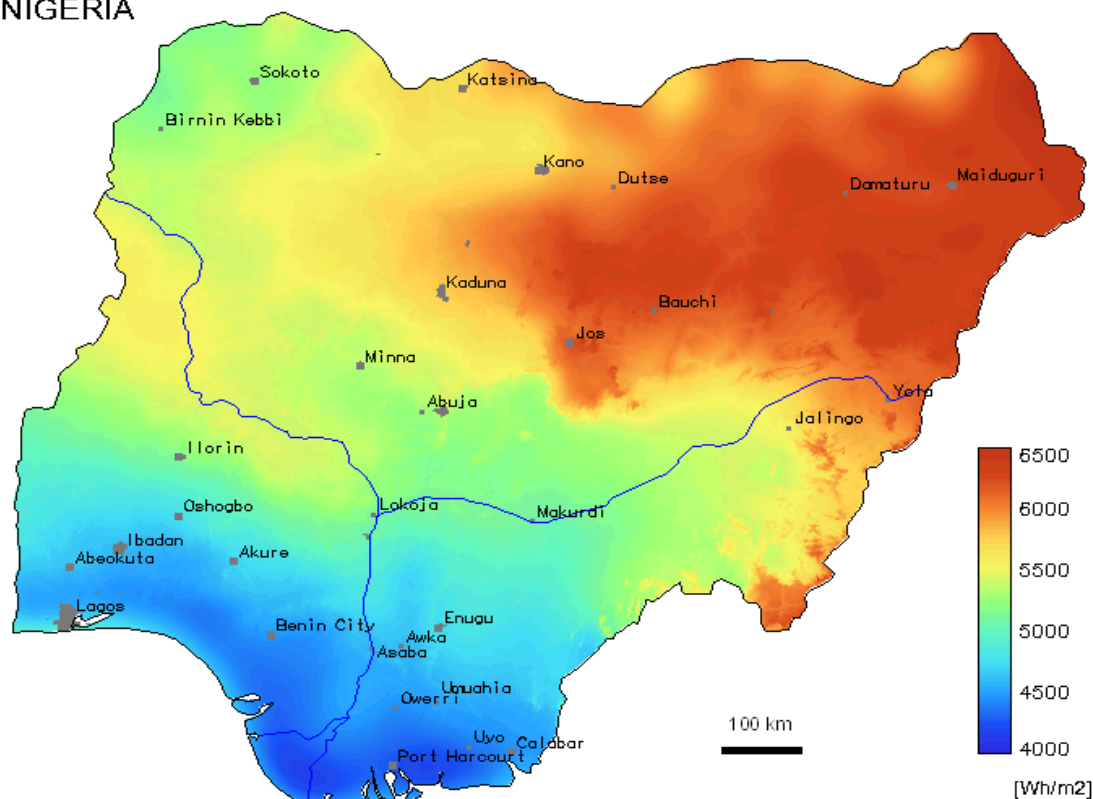
Aside from the indisputable advantages of solar energy mentioned above, the consideration of harnessing solar energy among all other alternative sources of energy sources to meet the needs, especially in developing countries, is based on well established visibility studies. Firstly, most of the countries 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 or erratic power supply; 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 dual powered refrigerator using electricity from the national grid and the power generated by photovoltaic. The system works on power from the grid system when there is supply of electricity and automatically switches to be powered by the PV whenever there is power failure from the grid system. A dry cell battery was built into the system to store charges and run the system at night or when there are no solar insolation and supply of electricity.

Yearly average of daily sums of global horizontal irradiation
(HelioClim-1/PVGIS data, period 1985-2004)



NIGERIA



PVGIS (c) European Communities 2002-2006
HelioClim-1 (c) Ecole des Mines de Paris/Armines 2001-2006

<http://re.jrc.ec.europa.eu/pvgis/>

Figure 2. Solar Insolation in Different States in Nigeria.

Judging from the review on applications of solar energy as an alternative source of energy, there is a widespread consensus that PV-refrigerator systems are economic and reliable solution for rural regions, regardless of the level of national development. In other sectors except for health sector, PV-refrigerator systems are also preferred for seasonal and occasional use in the cottage, villas and resorts place. Design conditions and operating performance of PV-refrigeration system are significantly affected by local atmospheric conditions. The detailed analysis of local weather data is required to assess the various aspects of PV-refrigerators, such as design capacity, operating performance, operating cost, etc. By definition, Photovoltaic (PV) is a technology that converts sunlight directly into electricity. With the global demand to reduce carbon dioxide emissions and the economic and reliable solution for rural regions as stated before, PV technology is gaining popularity as a mainstream form of electricity generation as it provides an independent, reliable electrical power source at the point of use, making it particularly suited to remote locations. For this reason, nowadays, the use of PV solar energy in refrigeration has been increasing in rural regions. The use of this technology in refrigeration brings about a Photovoltaic-powered refrigerator, which is a cooling appliance that operates completely with energy harnessed from the sun that has been converted to electricity through Photovoltaic (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 this refrigerating system 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. Moreover, the design conditions and operating performance of a PV-refrigeration system are significantly affected by local climatic conditions. Therefore, this work studied experimentally the performance of DC PV-refrigeration system in Lagos with an atmospheric temperature range of 25-33°C and lowest solar insolation range 4000-4500Wh/m². 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.

Photovoltaic vapour compression systems have predominated in the area of small medical refrigerators since their high cost can be justified in these applications. Various workers have presented different types of technologies for powering refrigerators for various applications. Harvey [1] investigated a regenerative version of the solar refrigerative cycle with approximately twice the COP and costed a 1tonne per day machine for use in Zambia. He submitted that this technology, whilst more energy efficient, is limited by its bulk and the possible need for maintenance of moving parts. Iloeje [2] developed and tested experimentally, ammonia - calcium chloride system in Nigeria, but it is not manufactured commercially. Saunier and Reddy [3] designed and developed a biomass fuelled device in Thailand. Neither Iloeje [2] or Saunier and Reddy [3] system was developed commercially. Ahmed *et al* [4] tested a continuous ammonia–water refrigeration system in the Sudan. The feed pump was electrically driven. The project was beset by technical difficulties which prevented successful operation. Hinotani [5] constructed and tested a purpose designed solar diffusion absorption refrigerator. The generator design was successful in that the solution pumping rate was near the optimum over the full range of generating temperatures. However, difficulties with the hydrogen flow rate were encountered, giving poor evaporation of the generated ammonia and an overall (solar) COP of less than 0.05. Ewert et al [6] carried out experimental evaluation of a solar PV Refrigerator with Thermoelectric, Stirling, and vapour compressor heat pumps. Mohamed and Samuel [7] 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 [8] presented an experimental study of a multi-purpose PV-refrigerator system. Kim and Ferreira [9] 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. They pointed out that the biggest advantage of using solar panels for refrigeration is the simple construction and high overall efficiency when combined with a conventional vapour compression system. After critical review of literatures, it was submitted that the most preferred solar system in the refrigerator is photovoltaic system applications [6, 9, 10]. Gadhia and Patel [13] investigated solar powered refrigerator with thermal storage, while Oko and Njoku [14] explored the performance of solar-powered refrigeration system using parabolic collector. Solar-powered picnic refrigerator was designed and developed by Adedeji et al. [15]. In recent times, there have been many researches on solar-powered refrigerators [16-24].

2. 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, Nigeria, where we have one of the least solar insolation in the Western Africa and in the month of July, when the solar insolation 4.04kWh/m^2 which is the least solar insolation in the state throughout the year, as shown in Table 1.



Figure 3. The Complete set-up of the Solar-Powered Refrigerator With Solar Tracker.

Table 1. Panel Module Specification.

PV-module	UE12MF5N
Cell Type	Monocrystalline silicon, 150mm^2
Dimensions	$1500 \times 665 \times 46\text{mm}$
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	1

3. RESULTS AND DISCUSSION

The cooling temperatures of the refrigerator were taken at an interval of 15 minutes for the solar refrigerator with and without, and also for the mains (AC) supply, as shown in Table 2.

Table 2. Panel Module Specification.

Time interval (mins)	Temp ($^{\circ}\text{C}$) of the Solar Refrigerating system without Solar tracker	Temp ($^{\circ}\text{C}$) of the System running on the AC from National Grid	Temp ($^{\circ}\text{C}$) of the Solar Refrigerating system with Solar tracker	Temp ($^{\circ}\text{C}$) of the System with Solar tracker Switched from Grid to Solar Refrigerator with tracker
0	27	27	27	27
15	21	19	21	19
30	17	12	15	14

45	12	9	11	10
60	6	4	5	5
75	1	0	0	0

An empirical model was derived for the temperature variation with time for the various speeds;

$$T(t) = \varphi + \chi t + \theta t^2 + \phi t^3 + \vartheta t^4 + \varrho t^5$$

Table 3. Constant Values for Mathematical Models of Temperature-Time Variation for Powering Sources.

Powering Sources	ϱ (C/s ⁵)	ϑ (C/s ⁴)	ϕ (C/s ³)	θ (C/s ²)	χ (C/s)	φ (C)
AC	1.975x10 ⁻⁷	-3.73x10 ⁻⁵	2.37x10 ⁻³	-5.61x10 ⁻²	-0.11	27
Solar Ref. without Solar tracker	1.0974x10 ⁻⁸	4.1152x10 ⁻⁶	-4.5679x10 ⁻⁴	1.91x10 ⁻²	-0.5967	27
Solar Ref. with Solar tracker	1.427x10 ⁻⁷	-2.634x10 ⁻⁵	-1.667x10 ⁻³	-4.74x10 ⁻²	-0.082	27
Temp (°C) from the System with Solar tracker Switched from Grid to Solar	3.292x10 ⁻⁸	-4.938x10 ⁻⁶	-1.605x10 ⁻⁴	5.6x10 ⁻²	-0.638	27

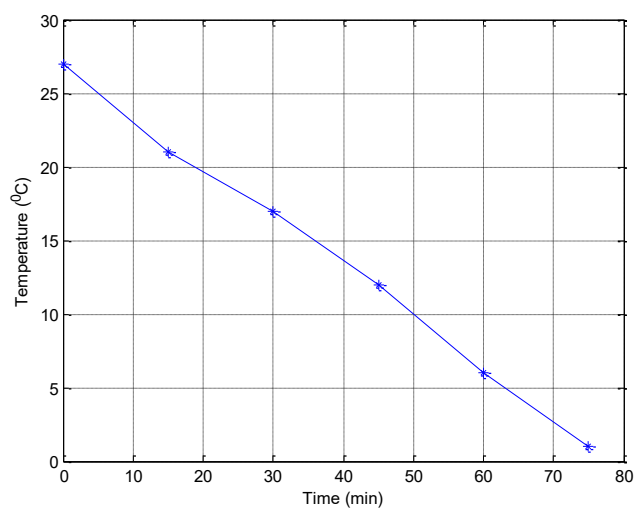


Figure 4. Temperature Variation with Time for the Refrigerator System Powered by PV Panel Without a Solar Tracker.

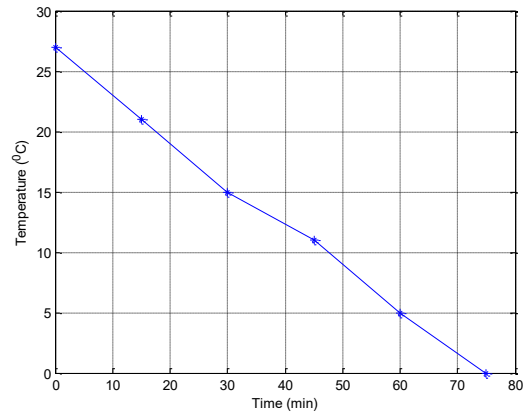


Figure 5. Temperature Variation with Time for the Refrigerator System Powered by PV Panel with Solar Tracker.

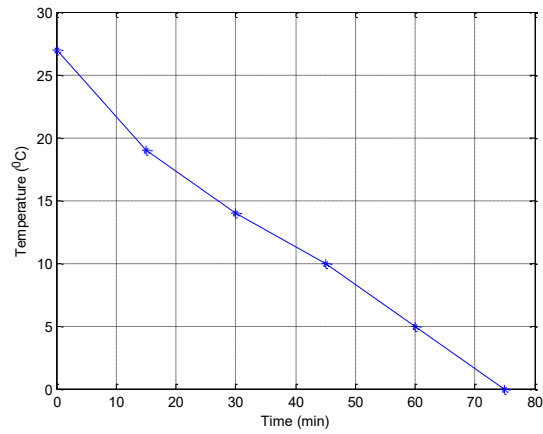


Figure 6. Temperature Variation With Time for the Refrigerator System Powered by a Switchable Power Source With Solar Tracker.

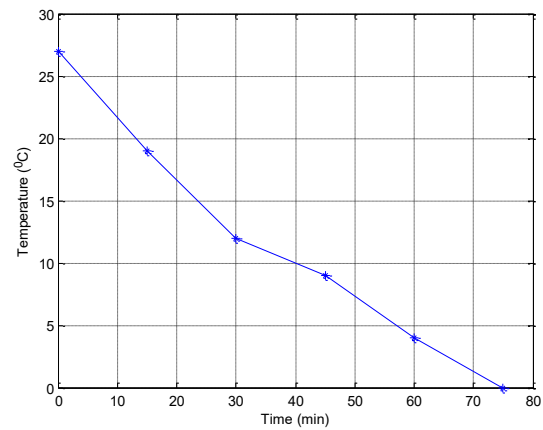


Figure 7. Temperature Variation With Time for the Refrigerator System Powered by Electricity from the National Grid.

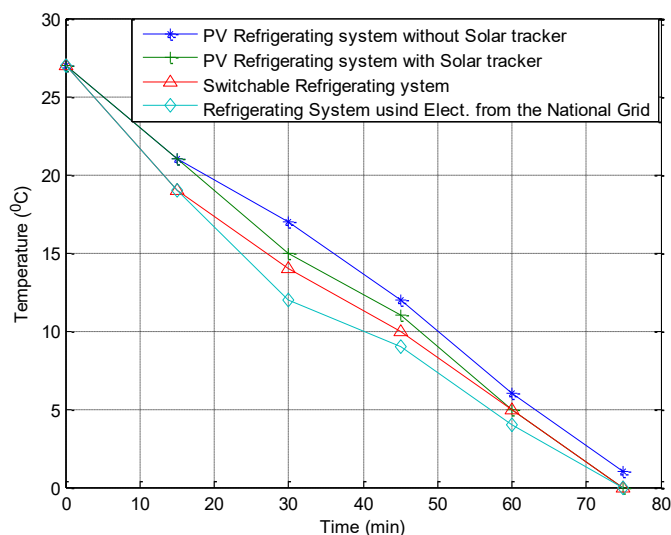


Figure 8. Comparison of Temperature Variation Over Time for the Refrigerator System Powered from Different Sources.

4. CONCLUSION

In order to address the needs of the majority of rural communities in several African countries, particularly Nigeria, which have unpredictable and irregular electricity sources, a dual-powered refrigerator (using solar energy and electrical energy from the national grid) was designed and developed in this work. The refrigerator was designed to run on the national grid and to automatically switch to solar power in the event that the national grid fails. 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 was recorded. The testing of Refrigeration system in a State in Nigeria with one of the lowest atmospheric temperature ranges of 25-33°C and lowest solar insolation range 4000-6000Wh/m² 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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