Solar Energy for Cooking and Power Generation: An Analysis

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Abstract -Solar energy currently represents the most abundant inexhaustible, non-polluting and free energy resources that could be used economically to supply man's increasing energy demands. The economic importance associated with the use of solar energy for cooking and power generation outweighs that of using non-renewable fossil fuel as an energy source. This paper, therefore, presents the availability and analysis of solar energy for cooking and power generation. The technology involving the collection and conversion of solar energy into useful heat and electricity was discussed. The performance of the existing solar systems was analyzed to buttress the need to divert attention towards the utilization of the inexhaustible, abundant and non-polluting energy as a means of alleviating the energy problems. Thermal performance experiments were conducted in order to determine the First figure of merit (F_1), the Second figure of merit (F_2) and the Overall cooker thermal efficiency (η_u) which were determined to be 0.117Km^{2}w^{-1}, 0.47, and 38%, respectively. This performance shows that the cooker compare favourably well with international standard and therefore illustrates that the solar box cooker is very reliable for cooking and for hot water production. The paper also presents the economics of photovoltaic technology for power generation.

Key Words**Solar, Insolation, temperature, radiation, performance, energy, generation**

1.INTRODUCTION

Solar energy, a naturally abundant energy resource without any negative impact on the environment has gain attention of the academia and industrial actors over the past decades for supplementing the supply of ever increasing energy demand. The need for the use of solar energy for power supply is more prominent in the developing countries in Africa which happens to be the least electrified continent [Abdulkarim, 2005]. The utilization of solar energy depends on its availability and appropriate technology [1]. The sun radiates enormous amount of energy. It radiates energy in one year than people have used since the beginning of times [2,3]Photovoltaic (PV) electricity generation is a proven, commercially available technology [2]

Since the beginning of civilization, the use of energy has been a key to survival. The utilization of energy depends on two factors; available resources an appropriate technology. The major energy resources in use today are derived mainly from nuclear and fossil fuels. These sources of fuel are non-renewable and exhaustible and their explorations are quite expensive. In most developing countries, wood has been the major fuel for cooking, roasting and baking. Apart from the high cost of fuels like kerosene and gas, there is the problem of distribution, which most times prevent people in the cities and rural areas from getting access to them. The economic importance associated with domestic heating by solar energy as the source of heat, outweighs that of using non-renewable fossil fuel as an energy source [1].
The high cost of modern day exploration techniques coupled with the devaluation of currencies of most developing countries like Nigeria has made the price of fuel so high that most homes cannot afford it anymore. The coming of modern civilization has increased the standards of living of most people and has as well increased the demand for fossil fuels and electricity, thereby further increasing its cost. The increase in population has increased the demand for wood fuel and this has caused a lot of deforestation, which has resulted in serious desert encroachment. This paper therefore, discusses the need to harness the abundant solar energy to reduce the over dependence on fossil fuels.

1.1 Availability of Solar Energy in Nigeria

To evaluate the economics and performance of systems for the utilization of solar energy in a particular location, knowledge of the available solar radiation at that place is essential. Thus, the utilization of solar energy, as with any other natural resources, required detailed information on the availability.

The availability of solar radiation on the earth's surface is a function of geographical zone. The regions lying between 15° and 35° latitude north and south seems to be most favorably located. They have relatively little rains and clouds so that over 90% of the incident sunshine are direct radiation and the yearly sunshine hour is usually over 3000. The next most favorable region is the equatorial belt from 15°S to 15°N, which receives about 2800 hours of sunshine per year with very little seasonal variation. The high humidity and frequent clouds in this belt generally result in high proportion of the solar radiation taking from scattered radiation. Nigeria, lying approximately between 4°N and 13°N, is a geographically favorable zone for harnessing solar energy. On the average, the yearly total solar energy falling on a horizontal surface in Nigeria is 2300 kWh/m^2. The average sunshine hours per year are about 2500 hours. From the average amount of solar energy reaching the country, it is evident that the development of solar technology will be worthwhile

1.2 Solar Collection and Conversion
1.2.1 Photovoltaic Panel Technologies

The main Solar PV panel technologies are Hybrid, Monocrystalline, Polycrystalline and Amorphous. They vary in performance and cost which are two main item considered when selecting a PV technology. Also of importance is the area available for the panel.

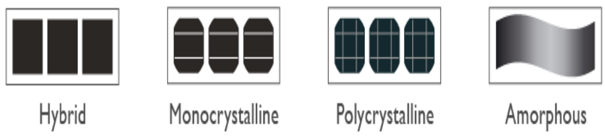

Figure -1: Solar Photovoltaic Technologies [2]

1.2.2 HYBRID PV MODULES

These modules are made up of amorphous and crystalline cells which gives it best all round performance. Although the initial cost is higher compared to other technology, hybrid PV panels generate better output per area (m^2), more kWh per year with consequent reduced payback period. Its performance is 900 kWh/kWp.

Figure -2: Hybrid PV Panels [2]

1.2.3Monocrytalline PV modules

They are high efficient, economic and reliable PV cells cut from a single crystal of silicon. Usually consider as the workhouses of the PV market as a result of their reliability and performance. The performance is put at 800 kWh/kWp.
They have uniform appearance and usually dark blue or black in colour.

Figure -3: Monocrystalline PV panels [2]

1.2.4 POLYCRYSTALLINE PV

Polycrystalline is a low cost, low performance PV cells cut from multifaceted crystalline silicon and they are distinguished by their crystalline structure. They provide lower output when compared to monocrystalline panels. The performance is put at 750 kWh/kWp.

Figure -4: Polycrystalline PV panels [2]

1.2.5 AMORPHOUS PV PANELS

Having the lowest efficiency although good performance, amorphous PV requires a significantly more space to achieve the same comparative output as other technologies. This makes them more expensive and the performance is 850 kWh/kWp.

Figure -5: Amorphous PV panel [2]

1.2.6 FLAT PLATE COLLECTOR

Solar energy can be easily converted into heat and could provide a significant proportion of the domestic cooking and hot water demand in many countries. The most widely known and understood method for converting solar energy into heat is by the use of a flat plate collector for heating water, air or other fluids. It is simply a photon absorber, which converts photon to heat. It is non-directional in the sense that a photon arriving from any direction can be absorbed.

The term flat plate is somewhat misleading and is used to describe a variety of different collectors which have combination of flat, grooved and corrugated shapes as the absorbing surface, as well as various methods for transferring the absorbed solar radiation from the surface of the collector to the heat fluid. The flat plate collector is usually made of galvanized iron sheet paint black. This is to approximate a black body, which is the best absorber of solar radiation.

1.2.7 NON-TRACKING REFLECTING AND CONCENTRATING SYSTEMS

For any practical solar power scheme, the solar radiation has to be concentrated by a factor of about ten or more to achieve high temperatures. It is usually of considerable advantage if a stationary collector could achieve the required concentration. The Compound Parabolic Concentration (CPC) is an important class of concentrators. Concentrating factor of up to ten can be achieved without diurnal tracking and for lower factors, in the order of three, seasonal adjustments may not be needed. The efficiency for accepting diffuse radiation is much larger than for conventional focusing collectors. The axis of each parabola is inclined to the vertical optic axis. Heat collection is achieved by adding a cylindrical black body collector at the base of the parabolic array.

1.2.8 SOLAR COOKING AND HEATING

A solar cooker is a device which uses the energy of direct sunlight to heat, cook or pasteurize food or drink. Many solar cookers presently in use are relatively inexpensive, low-tech devices, although some are as powerful or as expensive as traditional stoves,[4] and advanced, large-scale solar cookers can cook for hundreds of people [5]. Because they use no fuel and cost nothing to operate, many non-profit organizations are promoting their use worldwide in order to help reduce fuel costs (especially where monetary reciprocity is low) and air pollution, and to slow down the deforestation and desertification caused by gathering firewood for cooking. Solar cooking is a form of outdoor cooking and is often used in situations where minimal fuel consumption is important, or the danger of accidental fires is high, and the health and environmental consequences of alternatives are severe.

A box cooker has a transparent glass or plastic top, and it may have additional reflectors to concentrate sunlight into the box. The top can usually be removed to allow dark pots containing food to be placed inside. One or more reflectors of shiny metal or foil-lined material may be positioned to bounce extra light into the interior of the oven chamber. Cooking containers and the inside bottom of the cooker should be dark-coloured or black. Inside walls should be reflective to reduce radiative heat loss and bounce the light towards the pots and the dark bottom, which is in contact with the pots. The box should have insulated sides. Thermal insulation for the solar box cooker must be able to withstand temperatures up to 150 °C (300 °F) without melting or out-gassing. Crumpled newspaper, wool, rags, dry grass, sheets of cardboard, etc. can be used to insulate the walls of the cooker. Metal pots and/or bottom trays can be darkened either with flat-black spray paint (one that is non-toxic when warmed), black tempera paint, or soot from a fire. The solar box cooker typically reaches a temperature of 150 °C (300 °F). This is not as hot as a standard oven, but still hots enough to cook food over a somewhat longer period of time. Panel solar cookers are inexpensive solar cookers that use reflective panels to direct sunlight to a cooking pot that is enclosed in a clear plastic bag.

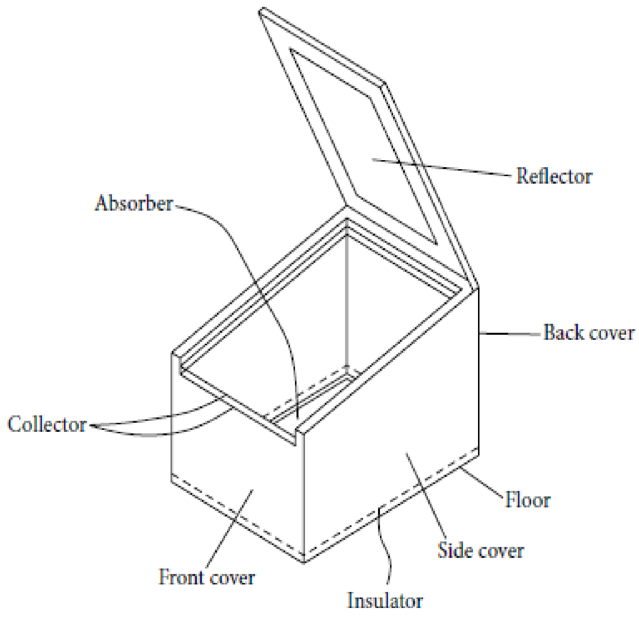

Figure -6: The Solar Box Cooker

A temperature of 110°C has been recorded and held for a long time with the design whose section is shown in Figure 6. The solar radiation is trapped in the box through the use of a flat plate collector painted black. The inside of the solar box is lined with reflecting material except the base, which is the collector. The solar box can be used to cook food for an average home of six in about two to three hours on a sunny day depending on the size of the box built.

Apart from this simple solar box, solar cookers are also built using parabolic reflectors for focusing and concentrating the solar radiation at the point of cooking. This point is usually the focal point of the parabola. Temperatures well over 100°C are obtained. The cooking here is done faster using the solar box because of the concentrating effect of the reflector.

2. PV PERFORMANCE

The performance of each of the technology is presented in Figure 6.

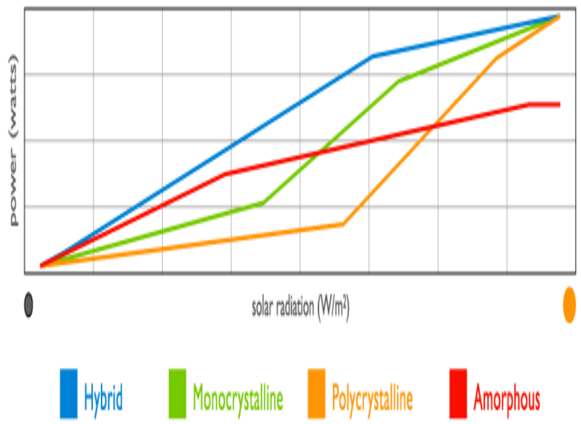

Figure 7: Graph illustrating comparative outputs of typical pv technologies based on amount of solar radiation

The performance of a PV panel is measured in kilowatt hours per kilowatt peak (kWh/kWp), which translates as the number of electrical units of energy (kWh) the panel will produce at maximum output (kWp), or in other words during the brightest sunlight. While this is a good measure of performance, it isn't the full story. Each technology performs differently in certain light conditions and considering our UK climate, overall performance becomes a significant factor.
The rated performance of a photovoltaic technology at full output does not necessarily reflect it's performance in less favourable light conditions. Hybrid technology is the best all round performer and will generate more electricity in lower light conditions than other technologies. Monocrystalline and Polycrystalline panels have a mid-range performance and are the most common type of photovoltaic panels. Amorphous technology, a flexible technology also known as Thin Film, is the least efficient technology requiring a significantly larger area than the other photovoltaic technologies [2].

2.1 .COST OF PHOTOVOLTAIC

Solar Energy (photovoltaic) prices have declined on average 4% per annum over the past few decades. This is not unconnected with technical advances, manufacturing innovations, progressive increase in conversion efficiencies and economies of scale in production [2].
The prices of solar panel in Nigeria is given below in the power rating of the PV.

- 80W solar panels: N38,500
- 130W solar panels: N62,000
- 140W solar panels: N67,000

- 160W solar panels: N76,000 [2]

The cost of solar panel will continue to drop with advancement and innovation in technology.

A residential solar energy system typically costs about \$8-\$10 per watt. Install cost can be as low as \$3 -\$4 per watt or 10-12 cent per kWh where government incentives programme exist combined with lower prices secured through volume purchase [4]. Without incentive programme, solar energy cost (in an average sunny climate) ranges between 20 – 44 cents/kWh for very large PV systems.

3. PERFORMANCE TESTING Difficulties in assessing numerous designs of solar cookers have led to the creation of three major testing standards for evaluating solar cookers throughout the world. They include: American Society of Agricultural Engineering (ASAE) Standard S580, The standard developed by the European Committee on Solar Cooking Research (ECSCR) and the Bureau of Indian Standards, based on work by [6]. Though, the three standards have their shortcomings, India standards provide testing standard based on thermal test procedures for box-type solar cookers. The performance of the reflector based solar box cooker implemented in this study was done based on India standard. The standard highlighted two methods of test: a stagnation test (test without load) and a load test. Test on the cooker was done when the solar irradiation was maximum [7]. The test was carried out between 10.00 am and 4.00 pm in order to determine the maximum plate and water temperature in the cooker at this period.

3.1 STAGNATION TEST

A number of tests without load were conducted on the cooker to determine its stagnation temperature and also to check the rise in temperature inside the cooker. The stagnation temperature, ambient temperature (Ta) and absorber plate temperature (Tp) were measured for different time of the day between 10:00 am and 4.00 pm during the operation of the cooker.

3.2 LOAD TEST

The loading test was done by placing a water-filled cylindrical pot covered by a lid, in the cooker. The test was conducted for three days with 1.0 kg of water in the first day, 1.5 kg of water in the second day and 2.0 kg of water in the third day. Each test was carried out on sunny day between 10:00am and 4:00pm daily.

3.3 Thermal performance measures

3.2.1 COOKING POWER ESTIMATION

Interval Cooking Power: The average cooking power, P is defined as the rate of useful energy available during heating period. It may be determined as a product of the change in water temperature for each interval and mass and specific heat capacity of the water contained in the cooking utensil. Dividing the product by the time (10-minute intervals according to American Society of Agricultural Engineers) contained in a periodic interval yields the cooking power in Watts:

$$P = \frac{(MC)_w (T_2 - T_1)}{600} \quad (1)$$

where$P$ is interval cooking power (W), T_1 is initial water temperature (∘C), T_2 is final water temperature (°C), M is mass of water (kg), and C is specific heat capacity (4186 J/kgK).

Standardized Cooking Power (P_s): To determine the standardizing cooking power, P_s from the cooking power, P, each interval is corrected to a standard insolation of 700W/m^2

$$P_s = \frac{P \times 700}{I_s} \quad (2)$$

whereP_s is standardized cooking power (W), P is interval cooking power (W), and $I_s$is interval average solar insolation (W/m^2).

First Figure of Merit The first figure of merit (F_1) of a solar box cooker is defined as the ratio of optical efficiency (η_O) and the overall heat loss coefficient (U_L)

$$F_1 = \frac{\eta_O}{U_L} \quad (3)$$

Experimentally:

$$F_1 = \frac{T_P - T_a}{I_S} \quad (4)$$

T_p, $T_a$and $I_s$are stagnation plate temperature, average ambient temperature and intensity of solar radiation respectively.

Second Figure of Merit The second figure of merit (F_2) is evaluated under full load condition and can be expressed by the expression given by [18], as follows:

$$F_2 = \frac{F_1 (MC)_w}{At} ln \left[\frac{1 - (\frac{1}{F_1})(\frac{T_{w1} - T_a}{I_s})}{1 - (\frac{1}{F_1})(\frac{T_{w2} - T_a}{I_s})} \right] \quad (5)$$

Where F_1 is first figure of merit ($Km^2 w^{-1}$), M_w is the mass of water as load (kg), C_w is the specific heat capacity of water (J/kg°C), Ta is the average ambient temperature (°C), $I_s$is the average solar radiation incident on the aperture of the cooker (W/m^2), T_{w1} is the initial water temperature (°C), T_{w2} is the final water temperature (°C), A is the aperture area (m^2) and t is the time difference between T_{w1} and T_{w2}

3.2.2 Overall Cooker Thermal Efficiency

The overall thermal efficiency of the solar box cooker is expressed mathematically by Olwi et al [8]

$$\eta_u = \frac{M_w C_w \Delta T}{I_{av} A_c \Delta t} \quad (6)$$

Where M_w is the mass of water (kg), $C_w$is the specific heat of water (J/kg/°C); ΔT is Temperature difference between the maximum temperature of the cooking fluid and the ambient air temperature; A_c is the aperture area of the cooker (m^2); Δt, is the time required to achieve the maximum temperature of the cooking fluid and I_{av}, the average insolation (W/m^2) during time interval.

4. RESULTS AND DISCUSSIONS

4.1 STAGNATION TEMPERATURE TEST

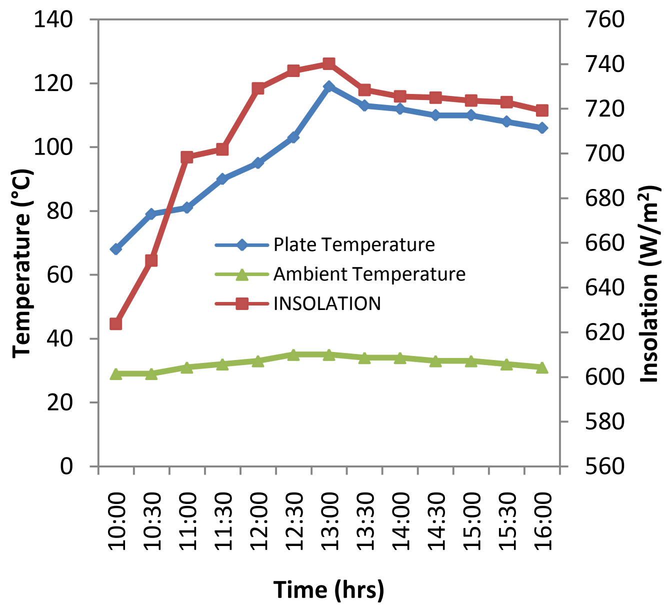

Figure -8: Stagnation Temperature Test

The result of stagnation temperature under no load condition is shown in Figure 8. The graph reveals the variation in the solar radiation and ambient temperature and their effects on the stagnation temperature observed in the absorber plate of the solar box cooker. The average ambient temperature for the test day was 32.38°C.

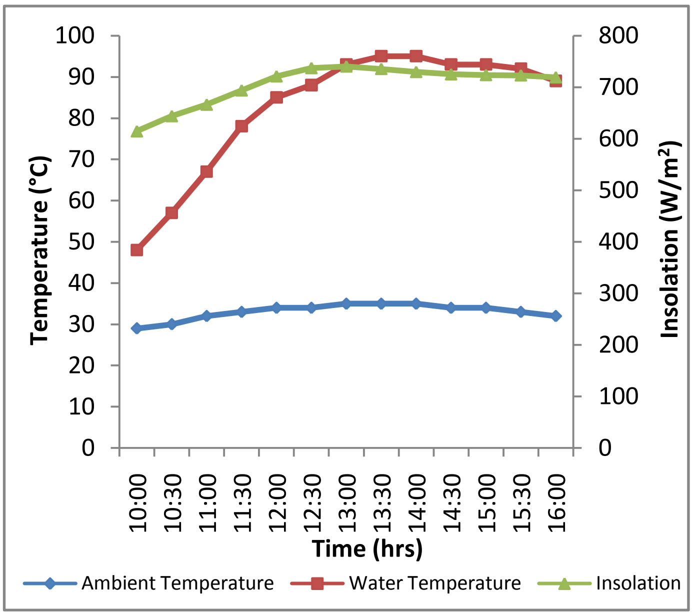

Figure -9: Thermal load test of the solar box cooker during sensible heat test of 1kg of water

Maximum absorber plate temperature of 109°C was recorded at 13:00hrs and at an insolation value of 740 W/m^2. The result shows that heat loss from absorber plate of the cooker is minimal and the absorber plate temperature is retained for a long time. This is desirable for heating water since major mode of heat transfer to the cooking vessels is by conduction from absorber plate.

Equation (4)was used to compute F_1. However, the obtained value is 0.117Km^2 w^{-1} where the allowed standard test states that if the value of F_1 is greater than 0.12, the cooker is marked as A-Grade and if less than 0.12 the cooker is marked as a B-Grade solar cooker [9]. The low value of first figure of merit is as a result of low optical efficiency and low insolation, as well as high convection and radiation loses from the cooker.

The thermal load test was conducted to determine the second figure of merit F_2 and it was evaluated under full-load condition. The solar box cooker was loaded with 1 kg of water at 48°C in an aluminium cooking vessel painted black; the water temperature was initially above the ambient temperature. Solar radiation, ambient air temperature, water temperature, and time were recorded at a regular interval till the water temperature exceeded 95°C.

The second figure of merit of the cooker (F_2) which corresponds to heat transfer efficiency of the cooker at low heat capacity of cooker interior is calculated to be 0.47 from sensible heat test (water heating test) of 1.0 kg of water in the cooker using equation (6) . The variation in the water temperature placed in the cooker was shown in Figure 9. In calculating the value of F_2, Bureau of Indian Standard [10] reported that some flexibility is allowed in the choice of T_{w1} and the time interval (t). Value of $T_{w1} > Ta$ was recommended byPurohit[11] while values of T_{w2} lower than the boiling point was recommended by Mullick[12]. The criteria for F_2 value by Indian standard is that F_2 should be greater than 0.42. The F_2 value of 0.47 obtained from this study compare favourably with the standard.

The Overall daily thermal efficiency of the solar box cooker (η_u) was calculated by equation (7) to be 38%

$$\eta_u = \frac{1 \times 4220 \times 33.6}{710.3 \times 0.036 \times 14400} \qquad (7)$$

The thermal efficiency calculated for the implemented cooker competes well with those found in the literature and this is an indication of better heat retention ability of the cooker.

5. CONCLUSIONS

The use of solar energy for cooking and power generation will reduce the over dependence on fossil fuels and the negative impact of tree felling on the environment. Solar power generation can be adopted during the dry season when water levels are usually low for hydropower generation. During this period, there is high availability of solar radiation owing to higher number of sunshine hours compared to other seasons that are favorable for hydropower scheme. Some parts of the Northern Nigeria like Nguru, Maiduguri, Yola and Sokoto can have solar power plants installed to supplement the existing power plants and to reduce long distance transmission. This will go a long way in alleviating the energy problems. The maximum solar radiation of 740 W/m^2 at 13.00 hours and Minimum of 246 W/m2 at 11.00 am were observed. The average ambient temperature observed during the period of test was 32.38°C. The performance of the cooker in terms of first figure of merit, second figure of merit and thermal efficiency show that the cooker compare favourably well with international standard. The cooker has a better heat retention capacity when compared with others found in the literature. The experimental results obtained for thermal performance of the cooker demonstrated its suitability for cooking even during fluctuating weather conditions.

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