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EVALUATION OF SOLAR CHIMNEY POWER PLANT IN SEMI-ARID REGION OF NIGERIA

Ngala, G.M[1*]., Oumarou, M.B[1]., Muhammad, A.B[1]. and Shuwa, M[2].
([1]Department of Mechanical Engineering, University of Maiduguri, Borno State, Nigeria
[2]Center for Entrepreneurial and Enterprise Development, University of Maiduguri, Borno State, Nigeria.)
*Corresponding author's e-mail address: garba.ngala68@gmail.com

Abstract

Solar chimney power plant (SCPP) is a renewable energy facility that converts the potential energy in the Sun into kinetic energy and subsequently into electrical energy. The problem of global warming and electricity generation/distribution in Nigeria cannot be over emphasized; however with the vast land in the semi arid region and the potentials of the above technology, high prospects exist for solar chimney as it is a decentralized form of power generation. The aim of this paper was to theoretically evaluate the performance of the solar chimney power plant in semi-arid region of Nigeria, and estimate the amount of electrical energy that can possibly be generated. A mathematical model was used to estimate the amount of power generated, and determine the relationship between various meteorological and physical factors to the power produced. A solar chimney power plant with collector diameter of 700 m and chimney height of 700 m can produce up to 3000 MW of electricity.

Keywords: Solar chimney power plant, semi-arid region, power generation, Nigeria

Nomenclature

A_{ch}	chimney cross-sectional area (m^2)
A_{coll}	collector area (m^2)
C_p	specific heat capacity (kJ kg^{-1} K^{-1})
F_R	collector heat removal factor
F'	collector efficiency factor
F''	collector flow factor
g	gravitational acceleration (m s^{-2})
q	solar radiation (W m^{-2})
H_{ch}	chimney height (m)
$\dot{m}$	mass flow rate (kg s^{-1})
P_{tot}	useful energy contained in the airflow (kW)
$P_{t,m}$	maximum mechanical power taken up by the turbine(kW)
P_{out}	electric output from the solar chimney (kW)
$\dot{Q}$	heat gain of air in the collector (kW)
T_a	ambient temperature (K)
T_{fm}	mean air temperature (K)
T_{in}	inlet air temperature (K)
T_{out}	outlet air temperature (K)
T_{pm}	mean plate temperature (K)
V_{ch}	air velocity at the chimney inlet (m s^{-1})
α	effective absorption coefficient of the collector
β	heat loss coefficient (W m^{-2} k^{-1})

η_{tot} total efficiency
η_{ch} chimney efficiency
η_{coll} collector efficiency
η_{t} turbine efficiency
ρ_{air} air density (kg m-^{3})
ΔP pressure difference produced between chimney base and the surroundings (Pa)
ΔT temperature rise between collector inflow and outflow

1. Introduction

The solar energy flux reaching the Earth's surface represents a few thousand times the current use of primary energy by humans. The potential of this resource is massive and makes solar energy an essential component of renewable energy portfolio aimed at reducing the global emissions of greenhouse gases into the atmosphere. However, the current use of this energy resource represents less than 1% of the total electricity production from renewable sources (GCEP, 2006). Only about 35% of Nigerians have access to electricity compared with 95% in Egypt and 75% in South Africa. On the overall, energy consumption in Africa is less than 5% of the global use. Though 13% of the world's populations and 10% of the world crude oil-reserves are in Africa, about 85% of the people in Africa still live in rural areas without access to electricity. Nigeria, the most populous country in Africa is herself facing an irony of sort; being the sixth largest world producer of crude oil, but yet facing very serious energy crisis for many decades (Ngala *et al.*, 2006). At present, the government is committed to finding a long-term solution to this crisis through the renewable energy master plan (REMP) with a target of increasing the present 5,000 MW to 16,000 MW by this year 2015 (ECN, 2007). The solar chimney power facility has the potential to become a valuable technology for renewable energy production, especially in countries with abundant solar radiation and large unused flat land. Solar chimney power plant, designed to produce electric power on a large scale, utilizes solar radiation to create air which drives the generator connected to turbines to produce electric power (Larbi *et al.*, 2010).

The idea of solar chimney dates back to 1903 when Isidoro Cabanyes, a Spanish artillery colonel wrote his book on solar chimney. This was followed up by Prof. Bernard Dubos who in 1926 proposed to the French Academy of Sciences the construction of a Solar Aero-Electric Power Plant in North Africa with its solar chimney on the slope of a high mountain (Marco, 2010). The first experimental prototype built was in Manzanares, Spain. It worked for 7 years thus proving the efficiency and reliability of this novel technology. The chimney height was 194.6 m and the collector had a radius of 122 m (Schlaich *et al.*, 2005).

A solar chimney power plant consists of a central chimney, surrounded by a solar collector that consists of a transparent canopy or roof supported a few meters above ground level, as shown in Figure 1. A turbine driving a generator is located at the base of the chimney. Solar radiation passing through the canopy strikes the ground below it from where heat is transferred to the adjacent air by means of convection. Due to buoyancy, the heated air flows towards the centre of the collector and then up the chimney where it drives the turbine.

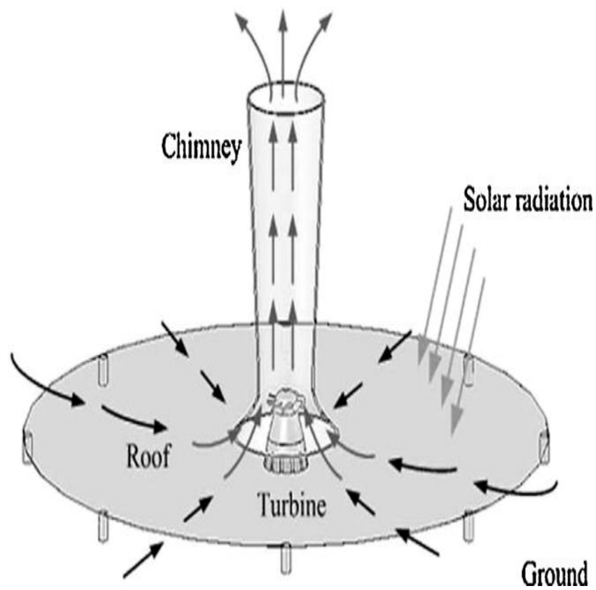

Figure 1: Solar chimney power plant schematic (Koonsrisuk and Chitsomboon, 2009)

Fundamental investigation of energy balance, design criteria and cost analysis of the prototype was conducted by Haaf *et al.* (1983). The following year, the same authors reported preliminary test results of the solar chimney power plant. Krisst demonstrated a ‘‘backyard-type’’ device with a power output of 10 W in West Hartford, Connecticut, USA. Kulunk produced a microscale electric power plant of 0.14W in Izmit, Turkey (Ming *et al.*, 2006). Many attempts have been made to evaluate the performance of solar chimney power plants in some parts of the world theoretically. Dai *et al.* (2003) concluded that a solar chimney power plant in Northwestern regions of China was able to produce 110–190 kW of electric power with a chimney height of 200 m and diameter of 10 m, and with a collector cover of 196,270 m^2.

Frederick and Reccab (2006) studied the potential of solar chimney power plant applications in rural areas. Nizetic *et al.* (2008) analyzed the potential for electric energy production in Mediterranean countries and estimated the quantity and price of the electric energy produced. Larbi *et al.* (2010) presented the performance analysis of a solar chimney power plant expected to provide the remote villages located in Algerian southwestern region with electric power. Zhou et al. (2010) developed a simple mathematical model based on energy balance to analyze the performance of solar chimney power plants in Qinghai-Tibet Plateau. Sangi (2012) presented performance evaluation of solar chimney power plants in Iran.

The semi-arid region of Northern Nigeria is endowed with an average solar radiation and sunshine hours of 7 kW/m^2/day and 9 hours respectively (Ngala *et al.*, 2013). To this should be added the fact that semi-arid regions are characterized by annual rain falls of 125 to 500 mm and average daily temperatures of 40-45^{o}C (SFSA 2007), which corresponds to the mesophilic temperature range, and are endued with enormous unused flat land. These conditions together make the semi-arid region and Maiduguri in particular very suitable for citing large scale solar chimney power plant. However the aim of this paper is to evaluate the performance of solar chimney in the semi-arid region of Nigeria.

2. Solar Chimney Power Plant (SCPP)

A SCPP consists of a solar hot air collector, a solar chimney and a turbine with generator. This unique combination accomplishes the task of converting solar radiation into electrical power. The solar-to-electric conversion involves two intermediate stages. In the first stage, conversion of solar energy into thermal energy is accomplished in the collector by means of the greenhouse effect. In the second stage, the chimney converts the generated thermal energy into kinetic and ultimately into electric energy by using a combination of a turbine and generator. Figure 2 provides an overall view of a typical solar chimney system. In its simplest form, the collector is a glass or plastic film cover stretched horizontally and raised above the ground. This covering serves as a trap for re-radiation from the ground. It transmits the shorter wavelength solar radiation but blocks the longer wavelength radiation emitted by the ground. As a result, the ground under the cover heats up, which, in turn, heats the air flowing radially above it. A flat collector of this kind can convert a significant amount of the irradiated solar energy into heat. The soil surface under the collector cover is convenient energy storage medium. During the day, a part of the incoming solar radiation is absorbed by the ground and is later released during the night. This mechanism is capable of providing a continuous supply of power all year round. The characteristics of the SCPP includes: (1) Low operation cost. (2) Cooling water is not required. (3) Construction technology is familiar, and materials are abundant and cheap. (4) Soil under the collector can act as natural energy storage system. (5) Both direct and diffuse solar radiations can be utilized for solar-thermal conversion. (6) The SCPP energy conversion efficiency is lower than other renewable energy power systems, but can be improved by increasing its dimension (Asnaghi and Ladjevardi, 2012).

3. Mathematical Expression of Solar Chimney Power Plant Performance Parameters

Factors affecting the performance of SCPP fall into two categories: the meteorological conditions and the structural parameters. The meteorological conditions include solar radiation, ambient temperature and wind speed. Structural parameters include the chimney height, the collector radius, chimney diameter, properties of the collector material and sand under the collector, as well as collector inlet gap. Also important for power generation are the wind turbine and the controlling system of the plant. Detailed analysis of heat transfer and fluid flow inside the solar chimney could be processed with Computational Fluid Dynamics software (Gannon and Backstrom, 2000; Backstrom and Gannon, 2000). Here, a simple method is reported, which takes into account solar collection, useful work and electric power output of the turbine, and is expected to evaluate the performance of the solar chimney power plant.

3.1 Total Efficiency

Total efficiency η_{tot} is determined here as a product of the individual component efficiencies:

$$\eta_{tot} = \eta_c.\eta_{ch}.\eta_t \qquad (1)$$

η_c is the efficiency of the collector, in other words, the effectiveness with which solar radiation is converted into heat, η_{ch} is the efficiency of the chimney and describes the effectiveness with which the quantity of heat delivered by the collector is converted into flow energy, η_t stands for the efficiency of the wind turbine generator (Sangi, 2012).

3.2 Solar Collector

A solar chimney collector converts available solar radiation q on the collector surface Ac into heat output. Collector efficiency η_c can be expressed as a ratio of the heat output of the collector as heated air $\dot{Q}$ divided by the product of solar radiation q (measured in W m^{-2}) times the area of the collector Ac.

$$\eta_c = \frac{\dot{Q}}{A_c q} \qquad (2)$$

Heat output $\dot{Q}$ at the outflow from the collector under steady conditions can then be expressed as a product of the mass flow $\dot{m}$, the specific heat capacity of the air C_p and the temperature difference between collector inflow and outflow ($T_{out} - T_{in}$):

$$\dot{Q} = \dot{m} C_p \left(T_{out} - T_{in}\right) \qquad (3)$$

where $\dot{m} = \rho_{air} V_{ch} A_{ch}$ (4)

Substituting Equation (4) into (3) and then (3) into (2) gives collector efficiency as

$$\eta_c = \frac{\rho_{air} V_{ch} A_{ch} C_p \left(T_{out} - T_{in}\right)}{A_c q} \qquad (5)$$

The ground which is covered by glass or other transparent materials, acts as a heat absorption layer. The periphery of the solar air collector is open to the atmosphere, and its central part is connected with the base of the solar chimney.

The energy balance equation is given as,

$$\dot{Q} = (\tau\alpha) A_c q - \beta A_c (T_{gm} - T_a) \qquad (6)$$

Substituting in equation (2)

$$\eta_c = \tau\alpha - \frac{\beta (T_{gm} - T_{in})}{q} \qquad (7)$$

Equating Equation (5) and (7)

$$V_{ch} = \frac{\tau\alpha A_c q - \beta\left(T_{gm} - T_{in}\right)A_c}{\rho_{air} A_{ch} C_p \left(T_{out} - T_{in}\right)} \tag{8}$$

This simple balance equation is independent of collector roof height because friction losses and ground storage in the collector are neglected. To evaluate collector performance, it is necessary to know the mean fluid (T_{fm}) and mean ground temperature (T_{gm}) (Sangi, 2012), which could be estimated by the method recommended by Duffie and Beckman (1991).

$$T_{gm} = T_{in} + \frac{\dot{Q}\left(1 - F_R\right)}{F_R A_c \beta} \tag{9}$$

$$T_{fm} = T_{in} + \frac{\dot{Q}\left(1 - F^{"}\right)}{F_R A_c \beta} \tag{10}$$

where the collector heat removal factor (F_R) can be expressed as

$$F_R = \frac{\dot{m} C_p}{A_c \beta}\left(1 - \exp\left(-\frac{A_c \beta F^{'}}{\dot{m} C_p}\right)\right) \tag{11}$$

Also the collector flow factor ($F^{"}$) is defined as the ratio of collector heat removal factor (F_R) to collector efficiency factor ($F^{'}$).

$$F^{"} = \frac{F_R}{F^{'}} \tag{12}$$

The mean fluid temperature is eventually required to solve the model, which could be found from the arithmetic mean of the inlet temperature and the mean ground temperature.

$$T_{fm} = \frac{T_{in} + T_{gm}}{2} \tag{13}$$

3.3 Solar Chimney

The chimney itself is the plant’s actual thermal engine. It is a pressure tube with low friction loss (like a hydro power station pressure tube or pen stock) because of its favorable surface-volume ratio. The updraft velocity of the air is approximately proportional to the air temperature rise (ΔT) in the collector and to the chimney height. In a multi-megawatt SCPP the collector raises the air temperature by about 30 to 35 K. This induces an updraft velocity in the chimney of (only) about 15 m/s at nominal electric output, as most of the available pressure potential is used by the turbine(s) and therefore does not accelerate the air. It is thus possible to enter into an operating solar chimney power plant for maintenance without danger from high air velocities. Hence the chimney efficiency is expressed as ratio of the output power to the solar heat gains.

$$\eta_{ch} = \frac{P_{tot}}{\dot{Q}} = \frac{g H_{ch}}{C_P T_a} \tag{14}$$

This simplified representation explains one of the basic characteristics of the solar chimney, which is that the chimney efficiency is fundamentally dependent only on chimney height (Schlaich *et al.*, 2005 and Sangi, 2012). Flow speed and temperature rise in the collector do not come into it. Thus the power contained in the flow from Eqn. (14) can be expressed as follows with the aid of Eqns. (3) and (4):

$$P_{tot} = \dot{Q}\eta_{ch} = \frac{gH_{ch}}{T_a}\rho_{air}V_{ch}A_{ch}\left(T_{out} - T_{in}\right) \tag{15}$$

A pressure difference ΔP is produced between chimney base (collector outflow) and the surroundings:

$$\Delta P = \rho_{air} gH_{ch}\frac{\Delta T}{T_a} \tag{16}$$

3.*4. Turbine*

The wind turbine generator fitted at the base of the chimney converts free convection flow into rotational energy. Turbines in a solar chimney do not work with staged velocity as a free running wind energy converter, but as a cased pressure-staged wind turbo generator, in which similar to a hydroelectric power station, static pressure is converted to rotational energy using a cased turbine. The mechanical power taken up by the turbine is given by the following expression;

$$P_{tm} = \frac{2}{3}\eta_C\eta_{ch}A_C q \tag{17}$$

This equation can further be expressed as

$$P_{tm} = \frac{2}{3}\eta_C\frac{gH_{ch}}{C_P T_a}A_C q \tag{18}$$

If P_{tm} is multiplied by η_t which contains both blade transmission and generator efficiency, this produces the electrical power from the solar chimney to the grid,

$$P_{out} = \frac{2}{3}\eta_t\eta_C\frac{gH_{ch}}{C_P T_a}A_C q \tag{19}$$

It is recognized that the electrical output of the solar chimney is proportional to $H_{ch}A_c$, i.e. to the volume included within the chimney height and the collector area. Thus, the same output can be achieved with different combinations of chimney height and collector diameter (Schlaich *et al.*, 2005 and Sangi, 2012). There is no physically optimum size. Optimal dimensions can be determined only by including the cost of the individual components (collector, chimney, mechanical components) at a particular site.

4. Results and Discussion

The mathematical expressions developed for the plant performance indicators were computed using some parameters that are given in Table 1. Figure 2 shows the effect of solar radiation on power output and Figure 3 shows the effect of collector radius on the generated power at a constant insolation of 800 W/ m^2. The effect of chimney height on plant performance is shown in Figure 4. It can be noted that the power production increases with the increase in the chimney height and solar radiation. The relationship of both chimney height and solar radiation with power produced is linear, while the relationship between collector radius and power produced is non linear as shown in Figures 2, 3 and 4 respectively. Figure 5 shows the profile of solar radiation and temperature at the site of interest and Figure 6 is the monthly average daily solar radiation in six locations of the semi-arid region.

Table 1: Technical data used in the analysis of solar chimney power plant performance.

Parameters	Value	Parameters	Value
Chimney height	700 m	Collector efficiency (η_c)	0.65
Chimney diameter	10 m	Solar radiation (q)	800 W/m^2
Collector diameter	700 m	Ambient temperature	35^o C
Turbine efficiency (η_t)	0.8	Distance from ground to collector cover	2.5 m

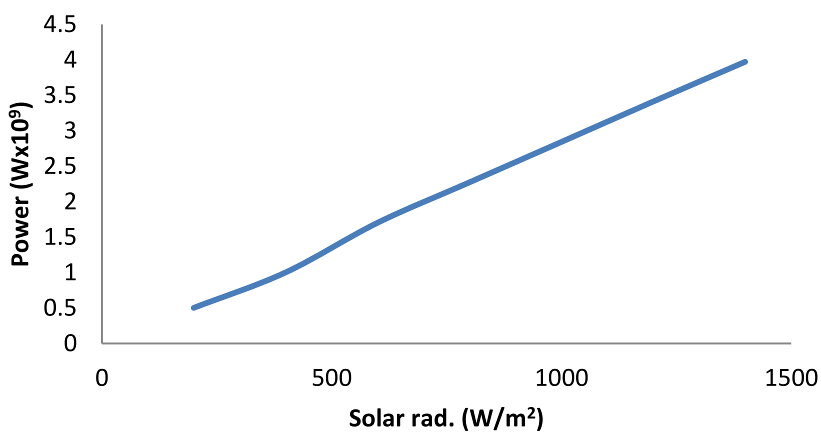

Figure 2: Effect of solar radiation on solar chimney power plant power output

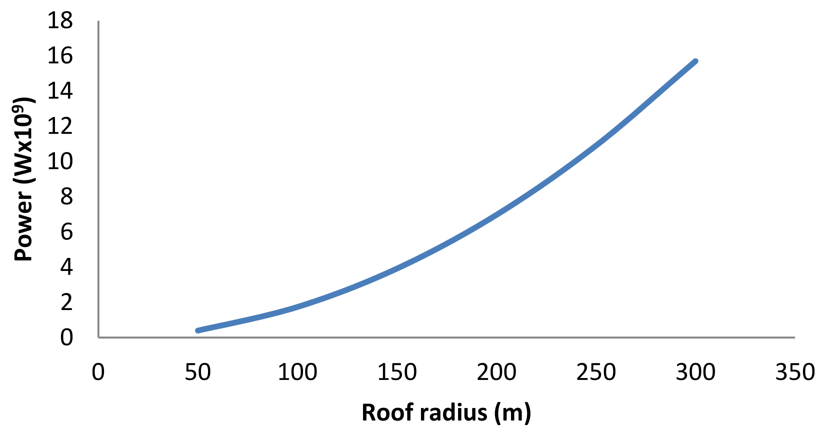

Figure 3: Effect of plant collector radius on power output for a constant insolation of 800 W/m^2

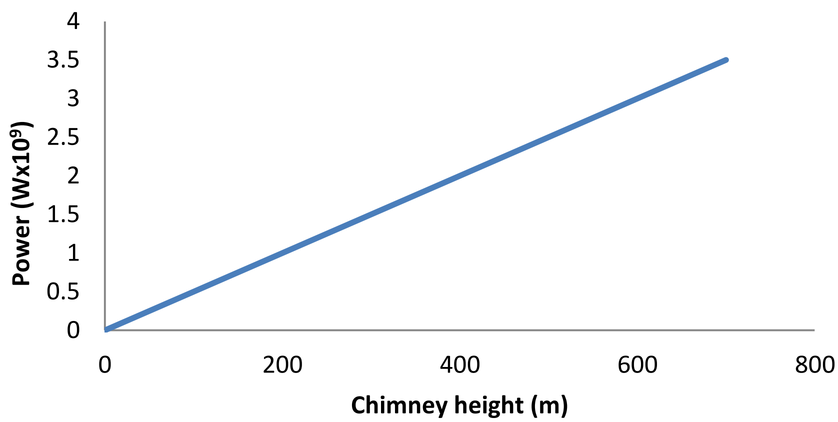

Figure 4: Effect of Chimney height on power output for insolation of 800 W/m^2

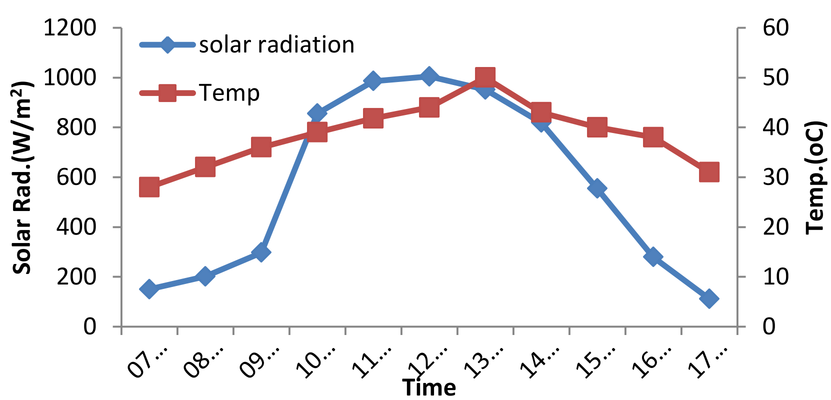

Figure 5: Solar radiation and Temperature profile for 8thof April, 2012 in Maiduguri

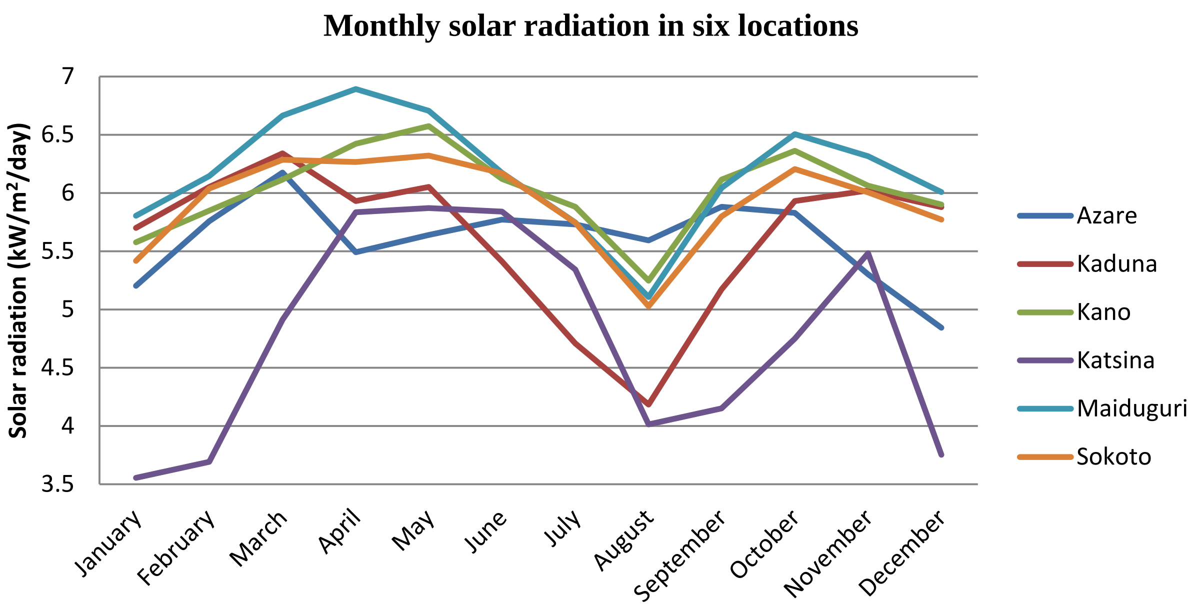

Figure 6: Monthly average daily solar radiation in six locations. (Fadere, 2009)

5. Conclusion

The intention of this study which was to evaluate the performance of solar chimney power plants in semi-arid regions of Nigeria theoretically and to estimate the quantity of the produced electric Power has been achieved. Mathematical models based on the energy balance were used to estimate the power output of solar chimneys as well as examine the effect of various ambient conditions and structural dimensions on the power output. A solar chimney power plant with 700 m chimney height and 700 m collector diameter is capable of producing monthly average 3000 MW electric power over a year. The capacity of power generation is dependent on ambient conditions and structural dimensions such as solar irradiation, ambient temperature, chimney height and collector diameter. The power generation capacity increased with the increase in solar chimney height and solar collector area. Also, the higher the solar radiation is, the greater the power generation.

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