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POTENTIAL OF SOLAR CHIMNEY POWER FOR RURAL ELECTRIFICATION IN GHANA

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Abstract— **The solar chimney power plant (SCPP) also known as 'solar updraft tower' is natural draft device that converts solar radiation into thermal energy to heat the in-flowing air under the collector roof and subsequently converts the thermal energy into kinetic energy through a caged wind turbine to produce electrical power.**

This paper presents the mathematical model analysis of the SCPP design and its potential for rural electrification in Ghana. The model was developed based on the energy balance to estimate the power output for some selected areas in Ghana. The solar chimney power plant with 400 m chimney height, 20 m chimney diameter and 1000 m collector diameter is capable of producing yearly between 62 - 91 MWh in the selected locations in Ghana across the three main geographical divide. The use of solar chimney power plant to promote rural power development in many locations in Ghana is possible especially in the northern belt. Solar energy is free, inexhaustible and environmentally benign and therefore the use of conventional energy sources, like crude oil and natural gas, for power generation can be reduced.

Key words – solar chimney, potential, electrification, Ghana.

1. NOMENCLATURE

A_{sc} **Area of solar chimney (m^2)**

A_c **Area of collector (m^2)**

C_p **Specific heat capacity of air (kJ/kg. K)**

d_{sc} **Chimney diameter (m)**

g **Acceleration due to gravity (m/s^2)**

G **Average monthly daily solar radiation on a horizontal surface** (W/m^2)

H_{sc} **Chimney height (m)**

$\dot{m}$ **Mass flow rate Kg/sec**

p_d **Dynamic pressure (N/m^2)**

p_s **Static pressure (N/m^2)**

P_e **Electrical power (MW)**

p_{sc} **Pressure in the solar chimney (N/m^2)**

P_{air} **Power in the flow (W)**

ΔP_{tot} **Total pressure in the flow (N/m^2)**

$\dot{Q}_u$ **Useful power (kW)**

T_a **Ambient air temperature (K)**

T_p **Absorber Plate temperature (K)**

$T_{2'}$ **The collector air outflow temperature (K)**

ΔT **Collector air temperature growth/rise (K)**

V_{sc} **Velocity of airflow through the chimney (m/s)**

V_m **Maximum airflow rate through the chimney (m/s)**

Greek symbols

ρ **Density of air (kg/m^3)**

η_c **Efficiency of collector**

η_{sc} **Efficiency of chimney**

η_{wt} **Efficiency of wind turbine**

η_t **Efficiency of turbine**

$(\overline{\tau\alpha})$ **Transmittance-absorptance product**

Abbreviations
SCPP- Solar chimney power plant

I. INTRODUCTION

Energy has been identified as the prime mover behind all forms of development and technological advancement. In areas such as industry, transport, health, education, sanitation, etc. energy plays an essential role in ensuring the quality of these services. Over the past decades there has been heavy and over reliance on fossil fuels in meeting global energy demands. This has resulted in issues such global warming, acidic rain, oil price hikes and fast depletion of finite mineral reserves especially oil and gas deposits. In finding lasting solutions to these problems, alternative energy or sustainable power developments are strongly been advocated/ proposed by governments and policy makers all around the globe to help reduce or mitigate this negative effect associated with the use of energy.

Ghana has a target to increase the share of renewable energy to 15 percent by the year 2015 in its energy mix. Although this target has not yet been achieved, but pragmatic steps have been outlined to promote the use of renewable energy. One of such major milestone was the promulgation of the renewable energy bill in 2011.

Geographically, Ghana benefits from renewable energy resources, which includes solar energy, wind, biomass and small hydropower. These resources amount to a total exploitable capacity between 460-560 MW [1]. These resources if harnessed could go a long way to mitigate the ailing power crisis, as well as promote rural power development.

The Solar Chimney Power Plant (SCPP), which employs both solar, and wind energy, is being accessed and investigated in meeting rural power demand in Ghana.

II. SYSTEM DESCRIPTION AND PRINCIPLES

The solar chimney power plant (SCPP) is a solar thermal technology made up of three major components, a solar collector, solar chimney or tower and a wind turbine illustrated in Fig. 1. Like any other invention, the idea of generating power using the SCPP was first proposed by Leonardo Da Vinci in the 15th century. Since then the SCPP had gone through many transformations and developments until 1982 when the first prototype plant was build in Manzanares in Spain by a German company Schlaich Bergermann and Partners (SBP). Literature review on SCPP can be obtained from [2].

The SCPP works by employing two main principles greenhouse effect and buoyancy. By green house effect the solar collector is able to generate heat by absorbing solar radiations to heat the air under the collector. By the principle of buoyancy, the heated air rises and flows radially through the solar chimney located at mid portion or centre of the collector, which intend drives a wind turbine fixed near the base of the chimney to produce power.

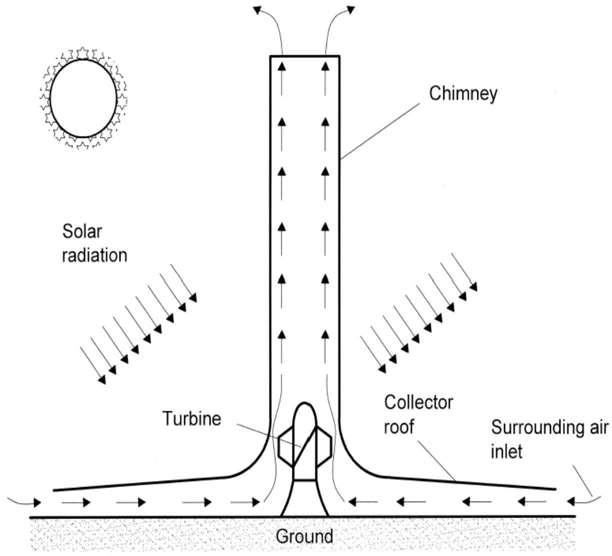


Fig. 1: A solar chimney power plant configuration.

III. MATHEMATICAL MODEL

A mathematical model of the plant has been developed based on the energy balance equation under the following assumptions.

1. Pressure loss due to friction in the chimney is negligible.
2. Airflow in the system is due to buoyancy force
3. The air flow in the collector is considered as a flow between two parallel plates [3]

A. The solar collector

The energy balance equation of the collector is given by Duffie and Beckman [4] as:

$$\dot{Q}_u = A_c\left[(\overline{\tau\alpha})G - U_L\left(T_p - T_a\right)\right]$$

The overall heat loss coefficient U_L for a single glazed collector can be obtained from the relation [5]

$$U_L = 5.5 + 0.024T_p \qquad (2)$$

The useful heat gain can also be expressed as

$$\dot{Q}_u = \dot{m}\, C_p\, \Delta T$$

Where $\dot{m}$ is the air mass flow given as:

$$\dot{m} = \rho_2 V_{sc} A_{sc} \qquad (4)$$

ΔT is the temperature rise between the hot air at collector outlet T_2 and the ambient temperature T_a At collector inlet By definition the collector efficiency is expressed as:

$$\eta_c = \frac{\dot{Q}_u}{A_c G} = \frac{\rho_2 V_{sc} A_{sc} C_p \Delta T}{A_c G} \qquad (5)$$

B. Solar chimney

The chimney is the plant's actual thermal engine. The main function of the chimney is to convert the heat flow produced by the collector $\dot{Q}_u$ into kinetic and potential energy.
The efficiency of the chimney is expressed as the heat-flow flow through the chimney to the heat-flow produced by the collector.

$$\eta_{sc} = \frac{P_{air}}{\dot{Q}_u} \qquad (6)$$

Where the power in the airflow is given as

$$P_{air} = \frac{1}{2}\dot{m}V_m^{\ 2} \qquad (7)$$

Given the maximum air flow speed through the chimney as

$$V_m^{\ 2} = 2gH_{sc}\left(\frac{\Delta T}{T_a}\right) \qquad (8)$$

Therefore combining Eq. (3), Eq. (7), Eq. (8), and substituting into Eq. (6), The efficiency of the chimney can therefore be expressed as a function of two key parameters, ambient temperature and the height of the chimney given by Schlaich (1995) [6] as

$$\eta_{sc} = \frac{P_{air}}{\dot{Q}_u} = \frac{gH_{sc}}{C_p T_a} \qquad (9)$$

The change in the air densities between the chimney base (collector outlet) and the surrounding induces a pressure difference, and this initiate's or drives the airflow through the chimney.
The total pressure developed between the chimney base and the surrounding is calculated as *[7]*

$$\Delta P_{tot} = \rho_2\, g\, H_{sc} \frac{\Delta T}{T_a} \qquad (10)$$

Where ρ_2 is the density of hot air flowing through the system (chimney)

The total pressure developed is a combination of the static pressure drop at the turbine ΔP_s and the dynamic pressure ΔP_d, which is converted into kinetic energy.

$$\Delta p_{tOt} = \Delta p_s + \Delta p_d \qquad (11)$$

In the absence of a wind turbine, a maximum airflow speed through the chimney is achieved and the total pressure difference is converted into kinetic energy to accelerate the airflow [8].

$$\Delta P_{tot} = \frac{1}{2}\rho_2 V_m^{\ 2} \qquad (12)$$

From Eq. (12) and Eq. (10) the maximum speed reached by the free convection air current in the chimney is therefore expressed as

$$V_m = \sqrt{\frac{2\Delta P_{tOt}}{\rho_2}} = \sqrt{2gH_{sc}\left(\frac{\Delta T}{T_a}\right)} \qquad (13)$$

In the case of turbine being on load, the maximum power is drawn when the chimney airflow rate velocity V_{sc} is one third of the maximum speed V_m.

Therefore the air velocity in the chimney V_{sc} is given as [9]:

$$V_{sc} = \frac{1}{3}\sqrt{2gH_{sc}\left(\frac{\Delta T}{T_a}\right)} \qquad (14)$$

C. Turbine

The maximum mechanical power taken up by the turbine is recommended by Schlaich, [10] as

$$P_{wt,} = \frac{2}{3} V_{sc} A_{sc} \Delta P_{tot} \qquad (15)$$

Substituting Eq. (5) and (10) into Eq. (15) gives

$$P_{wt,} = \frac{2}{3}\eta_c \frac{gH_{sc}}{C_p T_a} A_c G \qquad (16)$$

The maximum electrical power from the solar chimney is obtained by multiplying Eq. (16) by the wind turbine efficiency that contains both the blade transmission and generator efficiency. [11]

$$P_{e,} = \frac{2}{3}\eta_c \eta_{sc} \eta_{wt} A_c G \qquad (17)$$

IV. Results and Discussion

The performance of the SCPP was analysed based on the mathematical model expressed in the above equations. In other to obtain a the power output, the values in Table 1 were proposed based on land constraint and material availability for both the collector and chimney construction. The technical features of the SCPP in Table 1 together with the data from Fig. 2, and Fig.3 were used as input to the model.

Table 1: Design input and technical features of the SCPP.

Parameter	Value
Chimney height, Hsc	400 m
Chimney diameter,	10 m
Collector diameter,	4000 m
Collector roof height	2.5 m
Blade transmission and generator efficiency, η_{wt}	0.75
Ambient temperature, T_a	25 ℃
Temperature rise in the collector,	50 ℃
Single glass collector roof, Absorbance transmittance product	0.65

Fig.2 indicates the monthly average irradiance incident on a horizontal surface of the selected location measured by the Energy Commission of Ghana

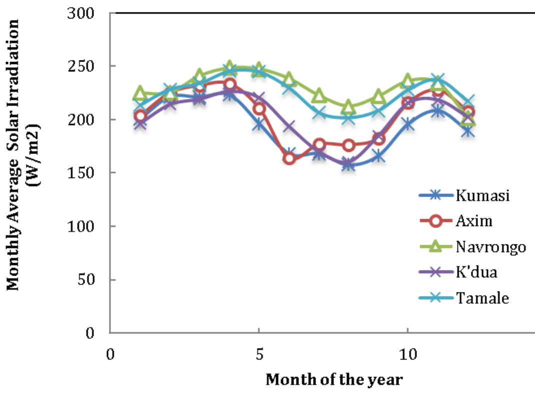


Fig. 2: Average monthly solar radiation intensity for selected locations [12]

Fig. 3 illustrates the average monthly temperature for each location measured 10 m from the earth surface by NASA.

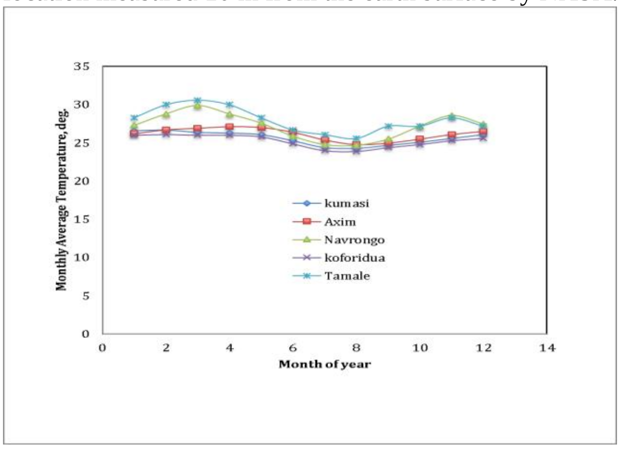


Fig. 2: Average monthly temperature selected locations [13]

Based on the input values, calculations were performed to solve the above equations together by iteration method for each of the five locations under study: Kumasi, Axim, Navrongo, Koforidua and Tamale to estimate for the average monthly power output.

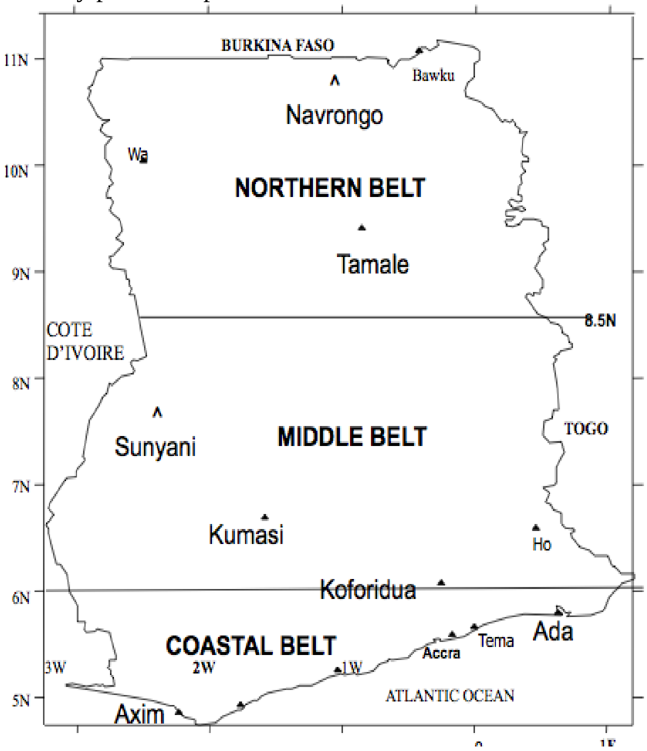
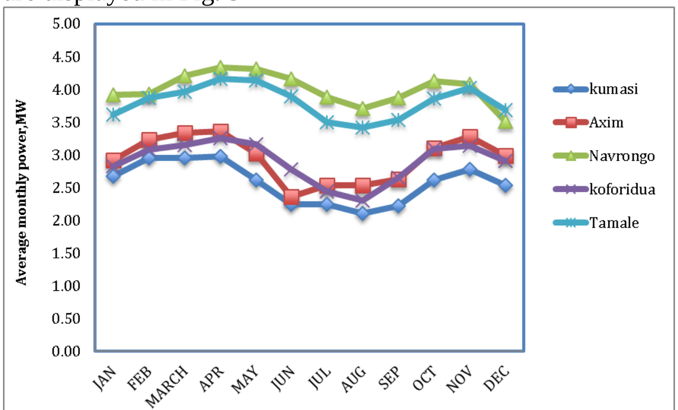


Fig. 4: Map showing the climatic regions of Ghana.

The locations were strategically chosen to cover the three main geographical and climatic regions in Ghana: coastal belts, the middle belt and the northern belt Fig. 4. The results are displayed in Fig. 5



Fig, 5 A comparison of power output produced in all locations

Generally the power output for each location was relatively high during the dry season as the solar radiations increased but the power output was found reducing from May to August, which are typical rainy season in Ghana.

A comparison of the power output produced in all locations illustrated in Fig. 5. Indicate that two towns in the northern belt i.e. Navrongo and Tamale produced the highest power output mainly as a result of the high solar irradiation. Axim in the costal region on the average showed a high power output as compared to the two cities in the middle belt Kumasi and Koforidua.

A variation of the average monthly power productivity and the irradiance is illustrated in Fig. 6. In all three geographical locations it was proven that the power productivity increases with an increase in the solar radiation intensity.

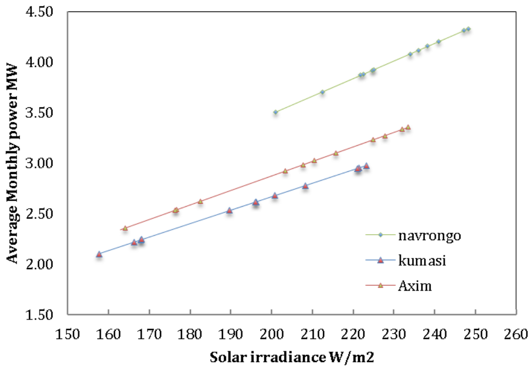


Fig.6: A variation in the average monthly power and the solar irradiance

The expected yearly energy that can be generated from the studied locations is shown in Fig. 7. From the graph it is clear that a substantial amount of energy can be generated from these locations especially in the northern belt with Navrongo on the lead with a potential of 96 MWh.

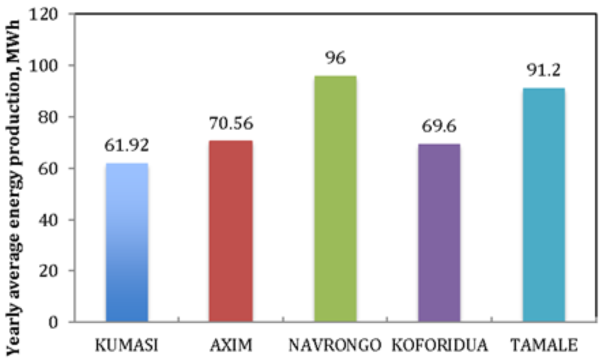


Fig.7 Yearly energy generated from studied locations

Generally all five locations show very promising results in the field of SCPP in Ghana. In the era where there are challenges in meeting our energy demands and same time expanding the national electrification access, the SCPP could be a way to promote rural power development. Solar energy is free, inexhaustible and sustainable therefore the use of conventional sources of energy, like oil and natural gas, for power generation can be reduced.

V. CONCLUSIONS

1. A SCPP has been analysed based on the mathematical model to predict the performance and its potential of power generation in some parts of Ghana, which covers all 3 main geographical locations: coastal, middle and northern belt.
2. It was observed that the power output produced in all locations comparatively was high during the dry season beginning from the month of October to May. The power produced reduced in the months of June to August as a result of the low temperatures recorded during the rainy season.
3. Navrongo, Tamale these two locations in the northern sector output the highest average monthly power generation of 4.33 MW and 4.16 MW respectively as a result of the high solar radiation intensities of a monthly average of 229.4 W/m^2 and 224.5 W/m^2.
4. The results obtained indicated that the power productivity of the plant in all three geographical locations increased with an increase in the solar irradiation.
5. From the results obtained an expected yearly energy in the range of 62 - 91 MWh can be generated from the studied locations. This is a very huge potential and substantially enough to promote rural power development. In the era where there are challenges in meeting our energy demands and same time expanding the national electrification access, the SCPP could be a way to promote rural power development especially in communities where the grid do not extend. Solar energy is free, inexhaustible and in abundance it is also environmentally benign and therefore the use of conventional sources of energy, like oil and natural gas, for power generation can be reduced.

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