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A Review of Solar Chimney Technology: Its' Application to Desert Prone Villages/Regions in Northern Nigeria

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Abstract— Electrical energy is an indispensable source of energy to livelihood especially in this 21th century. The carbon emission in the generation of electricity using fossil fuels is a major setback as this gas affects the climate. According to the statistics released by World Health Organization (WHO), direct and indirect effects of climate change leads to the death of 160,000 people per year and the rate is estimated to be doubled by 2020.

According to world energy council 2014 update, only 48% of the total population of Nigeria has access to electricity. Most of the people without electricity are people living in the rural areas of Nigeria. It is also estimated that 1.3 billion people are without access to electricity in the world and 87% of these people live in rural areas.

Solar energy is a renewable source of energy which is capable to producing electricity through different technologies. Solar chimney is one of the technologies used in producing electricity from solar energy. Although this technology is not is in commercial use in the world presently but research has shown that this technology is suitable for desert regions. This research is a review of this technology and how it can be applied to some desert prone villages in Nigeria.

Index Terms— Desert Prone Villages/Regions in Northern Nigeria, Renewable energy, Solar Chminey technology.

1 Introduction

CONSIDERING the rise in global energy demand and consumption, and also the threat of carbon emission, it is important to device alternative means by which energy is generated especially electrical energy. Electrical energy is a form of energy that is practically indispensable to the human race and the world at large. Preventing an energy crisis is one of the most crucial issues of the 21st century [7]. The environmental impact and the effect of carbon emission generated from the production of electrical energy from fossil fuel is a major threat to the human race. According to the statistics released by World Health Organization (WHO), direct and indirect effects of climate change leads to the death of 160,000 people per year and the rate is estimated to be doubled by 2020[8].

Solar energy is one of the few sources of energy that gives little or no carbon emission. Renewable energy sources like solar, wind, biomass, hydropower and tidal energy are promising CO_2 free alternatives [5, 6]. These renewable energy sources can provide sustainable energy services based on the utilization of routinely available indigenous resources. A transition from fossil fuels, natural gas and coal to renewable energy systems is increasing and likely; as their costs continue to decline while the cost of fossil fuels continues to rise. In the past 30 years, solar and wind power systems have continued to improve their performance characteristics and have experienced rapid sales growth [7]. In spite of several initiatives, policies, and investments for increasing generation capacity, the number of non-electrified areas in developing countries has not changed significantly. Lack of access to electricity continues to be one of the major reasons that citizens of non-electrified communities are still poor [4].

Solar chimney is one the techniques used in converting solar irradiance to useful solar power. According to Webster dictionary, a chimney is a vertical structure incorporated into a building and enclosing a *flue* or flues that carry off smoke; especially: the part of such structure extending above a roof [37]. It is suitable for power production in desert regions. The rest of this paper will look at how solar chimney can be applied to the desert prone villages in the northern region of Nigeria (Zamfara state) for electrical power production.

2.0 OVERVIEW OF NIGERIA SOLAR ENEGY POTENTIAL

Nigeria is one of the third world countries with the highest

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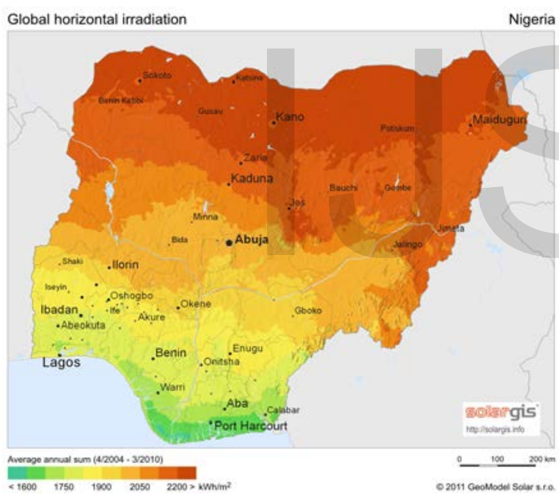
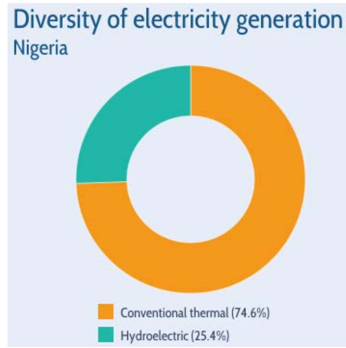
renewable energy potentials in the world. Although for most developing countries such as Nigeria specific solar data is not yet available like other countries. However, many attempts have been made to develop models that can predict the amount of solar radiation available at a given place from a few input parameters [9, 10, 11, 12, 13]. To this effect, NERC is currently exploring the resources available for sustainable power generation in Nigeria. They estimated an annual average of daily solar radiation to vary from as high as 7KW/m^2/day in the northern border regions to as low as 3.5KW/m^2/day in the coastal regions of south, and an annual average daily sunshine hours to vary from as high as greater than 8hrs/day in the northern border regions to as low as less than 6hrs/day in the coastal regions of south. It then classified the country with respect to availability of sunshine for Solar energy in to three classes; low, medium and high region [1]. For the developing countries (such as Nigeria) where there is an acute shortage of conventional source of energy, solar radiation data is still very scarce [10]. The solar irradiance for Nigeria is shown in the diagram below. The northern part of Nigeria enjoys solar irradiance as high as 2200Kwh/m^2 [15].

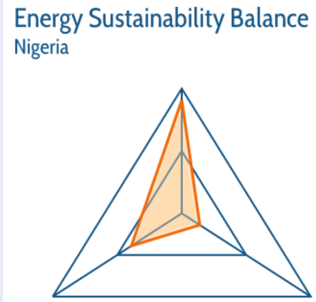


Solar irradiance view of Nigeria [15].

2.1 BRIEF REVIEW OF NIGERIA'S ELECTRICAL ENERGY SUPPLY

The non-utilization/under-utilization of renewable energy resources is highly visible on the energy production state of the country. According to Nigerian electricity regulatory commission, the current electrical production in Nigeria ranges between 3500-4000Megawatts and the current demand for electricity in the whole country has risen to 10,000Megawatts [14]. Most of the electricity generated in this country is from conventional thermal method and the other from hydropower, other means are very minute in terms of generation [9]. The diagram below shows the summary of Nigeria electricity production and also energy trilemma balance [9].



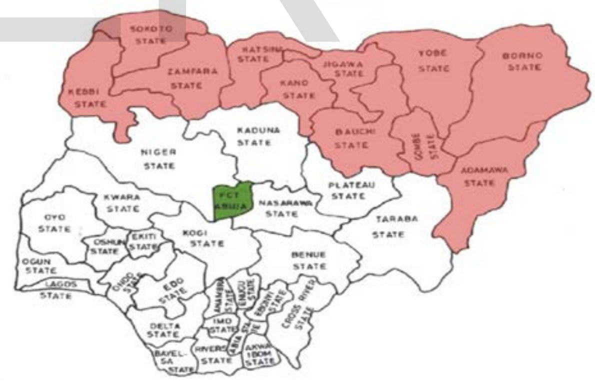


According to world energy council 2014 update, only 48% of the total population of Nigeria has access to electricity [9]. Majority of the people without access to electricity are in the rural area and desert region of Nigeria which has abundant solar irradiance. It is estimated that 1.3 billion people are without access to electricity in the world and 87% of these people live in rural areas [9].

2.2 DESERT PRONE REGIONS IN NIGERIA

Desertification, according to the Princeton University Dictionary is the conversion of grassland or an already arid land into a desert through indiscriminate human activities magnified by droughts. (Drought is a long period of dry weather in which there is not enough rain for successful growth of plants) [2,3].

About 11 states in Nigeria are desert prone already; these states are shown in the map below [3].



States prone to desertification in Nigeria.

3.0 SOLAR CHIMNEY OR SOLAR UNDRAFT TOWER

Solar chimney also known as solar updraft tower is a renewable (solar) energy technology for generating electricity. When solar radiation from the sun heats the air beneath a very wide greenhouse-like roofed collector structure surrounding the central base of a very tall chimney tower, the resulting convection causes a hot air updraft in the tower by the chimney effect. A wind turbines placed in the chimney updraft or around the chimney base is driven by the airflow and electricity is produced. Plans for scaled-up versions of demonstration models will allow significant power generation, and may allow development of other applications, such as water extraction or distillation, and agriculture or horticulture [19].

As a solar chimney power plant (SCPP) proposal for electrical power generation, high initial cost of building a very large novel structure is a discouragement for commercial investment, and the risk of investing in a feasible but unproven application of even proven component technology for long-term returns on investment—especially when compared to the proven and demonstrated greater short-term returns on lesser investment in coal-fired or nuclear power plants [19]. Likewise, the benefits of 'clean' or solar power technologies are shared, and the widely shared harmful pollution of existing power generation technologies is not applied as a cost for private commercial investment. This is a well-described economic trade-off between private benefit and shared cost, versus shared benefit and private cost. A solar hybrid system production of power was suggested by Professor Schlaich of Stuttgart university in the year 1978 [16].

3.1 BRIEF HISTORY OF SOLAR CHIMNEY

Although there may be earlier use or test of this technology but the first recorded proposal of solar chimney was done in 1903 by a colonel in the Spanish army Isidoro Cabanyes. He proposed a solar chimney power plant in the magazine *La energía eléctrica* [20]. Another early description was a publication by a German author Hanns Günther in 1931 [21]. Robert E. Lucier applied for patents on a solar chimney electric power generator in 1975; "between 1978 and 1981 patents (since expired) were granted in Australia, Canada, Israel, and the USA" [19].

The first small-scale experimental model of a solar draft tower was built in 1982 in Manzanares, Ciudad Real [22]. Manzanares is 150km south of Madrid, Spain at39°02′34.45″N 3°15′12.21″W. The power plant operated for approximately eight years and blew over [23]. This experiment setup did not sell energy.

Its height was 195 metres (640 ft) and its diameter was 10 metres (33 ft) with a collection area (greenhouse) of 46 hectares (110 acres) and a diameter of 244 metres (801 ft), obtaining a maximum power output of about 50 kW. Various materials such as single or double glazing or plastic were used for testing. One section was used as an actual greenhouse. Plastic material turned out to be less durable during this test. During its operation, 180 sensors measured inside and outside temperature, humidity and wind speed data was collected on a second-by-second basis [24].

Solar Chimney Manzanares view through the polyester collector roof

In December 2010, a tower in Jinshawan in Inner Mongolia, China started operation, producing 200 kilowatts [25, 26]. The 208 million USD project was started in May 2009 and intends to cover 277 hectares (680 acres) and produce 27.5 MW in 2013. The greenhouse is expected to improve the climate by covering loose sand, restraining sandstorms [27].

SUT powerplant prototype in Manzanares, Spain, seen from a point 8 km to the South

3.2 DESIGN

A typical solar chimney power plant consists mainly two parts:

- A solar up-drafting system that uses solar energy to create a constantly moving warm air stream (artificial wind). This system is consisting of a special solar collector (the greenhouse) and a tall cylindrical structure (the solar chimney) connected to the greenhouse.

- An electricity generating power system consisting of a set of air turbines that rotate forced by the previous warm air stream and generating electricity by means of the electric generators that are engaged to them (as special wind turbines).

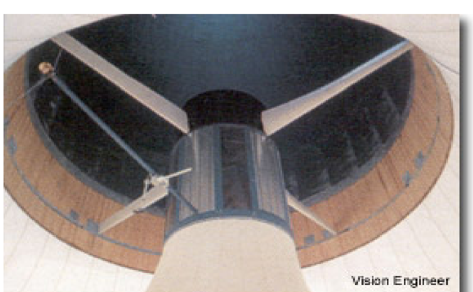
The Power output of a solar chimney system depends primarily on the collector area and chimney height. A larger area collects and warms a greater volume of air to flow up the chimney; the collector areas as large as 7 kilometres (4.3 mi) in diameter. A larger chimney height increases the pressure difference via the stack effect; chimneys can be as tall as 1,000 metres (3,281 ft) [28].

Heat is stored inside the collector area. The ground beneath the solar collector, water in bags or tubes, or a saltwater thermal sink in the collector could add thermal capacity and inertia to the collector. Humidity of the updraft and condensation in the chimney increases the energy flux of the system.

Collector of a solar chimney [17]

(Note that the base of the tower is the collector)

Turbines are placed horizontally in chimney, vertically in the collector. In order to obtain maximum energy from the warmed air, turbines blades should cover all the cross-sectional area of the chimney.



The turbine [17]

The CO_2 emitted during operations is negligibly [19]. Manufacturing and construction require substantial power, particularly to produce cement. Net energy payback is estimated to be 2–3 years [29].

Since solar collectors occupy significant amounts of land. Deserts and other low-value sites are most suitable for such a construction. A small-scale solar updraft tower will be an attractive option for remote desert regions in developing countries. The relatively low-tech approach could allow local resources and labour to be used for construction and maintenance [30].

The altitude of a tower increases the production of such tower. "Locating a tower at high latitudes could produce up to 85 per cent of the output of a similar plant located closer to the equator, if the collection area is sloped significantly toward the equator. The sloped collector field, which also functions as a chimney, is built on suitable mountainsides, with a short vertical chimney on the mountaintop to accommodate the vertical axis air turbine [30].

3.3 EFFICIENCY

The longer the chimneys height, the more the energy produced from the chimney. The efficiency of the chimney does not depend on the amount of the temperature rising as in most solar technologies, but depends on the outside temperature i.e. the difference between the ambient temperature and the temperature within the solar chimney system. Thus, the efficiency is directly proportional to the ratio between the height of the chimney and the outside temperature [31].

The solar updraft tower has a power conversion rate considerably lower than many other designs. Unlike Concentrated Solar Power or Concentrated Photovoltaic solar power plants that have efficiencies ranging between 20% to 31.25% (dish Stirling) respectively, the collector area is expected to extract about 0.5 percent, or 5 W/m² of 1 kW/m², of the solar energy that falls upon it. The efficiency of this technology ranges from 0.5% to 1% and this is a major setback for the technology in developed countries. Atmospheric winds and some other environmental factors can degrade the performance of the system.

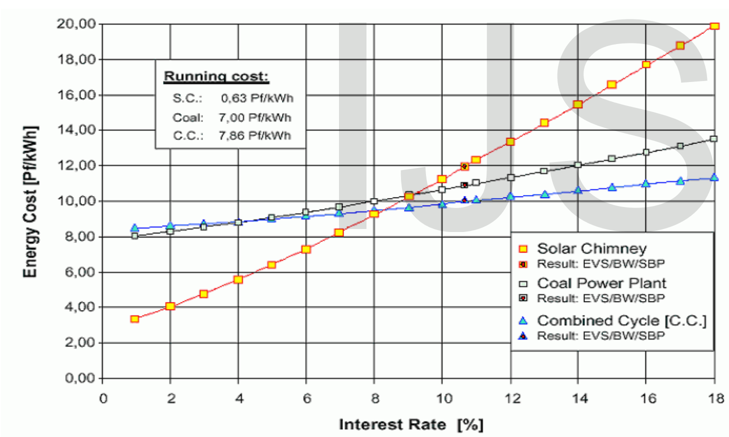
3.4 COST OF CONSTRUCTION

Constructing a solar updraft power station would require a large initial capital, but the operational cost for this technology is relatively low [29]. Compared to other renewable power sources, solar updraft power station doesn't require fuel and this is a plus in the operating cost.

The capital outlay of this technology is almost the same as that of the next-generation nuclear plants such as the AP-1000 and can be estimated as $5 per Watt of capacity. The total cost can be estimated as ranging from 7 (for a 200 MW plant) and 21 (for a 5 MW plant) euro cents per kWh to 25–35 cents per kWh [33] while approximately 3 Euro cents per KWh is the cost for a 100 MW wind or natural gas plant [34]. Since there is no commercial solar chimney power plant presently, no actual data are available for a utility scale power plant [35].

As with other solar technologies, some mechanism is required to mix its varying power output with other power sources. Heat can be stored in heat-absorbing material or saltwater ponds. Electricity can be cached in batteries or other technologies [36].

With the support of construction companies, the glass industry and turbine manufacturers a rather exact cost estimate for the construction of a 200 MW solar chimney could be compiled. "Energie Baden Württemberg" was able to determine the energy production costs compared to coal- and combined cycle power plants based on equal and common methods and this is shown the graph below [18]. The energy cost and interest rate of solar is considerably lower than coal power plant and combined cycle when in small quantity and vice versa.



Energy production costs from solar chimneys, coal and combined cycle power plants depending on the interest rate [18].

3.5 ADVANTAGES/DISADVANTAGES

- Solar chimney power stations are particularly suitable for generating electricity in deserts and sun-rich wasteland.

- Solar chimney is capable of providing electricity 24 hour a day from solar energy alone so no alternative system is needed for this system.

- No fuel is needed. It needs no cooling water and is suitable in extreme drying regions.

- It is particularly reliable and a little trouble-prone compared with other power plants.

- The materials concrete, glass and steel necessary for the building of solar chimney power stations are everywhere in sufficient quantities.

- No ecological harm and no consumption of resources.

- No operational carbon emission.

- Some estimates say that the cost of generating electricity from a solar chimney is 5times more than from a gas turbine. Although fuel is not required, solar chimneys have a very high capital cost.

- The structure itself is massive and requires a lot of engineering expertise and materials to construct.

- The size of land required for a solar chimney construction compared to the power output is not economical.

- It has low efficiency/conversion ratio.

4 APPLICATION TO DESERT PRONE REGIONS IN NIGERIA

According to the world energy council statistics in 2014, 1.3 billion people are without access to electricity and 87% of these people are in rural area [9]. As earlier discussed in this paper, solar chimney is very suitable for desert regions and villages with desert large expanse of land. Although solar updraft tower power plant is not yet in commercial operation in the world, but it has been proven that a 200MW capacity of this plant can power at like 200,000 houses and also can abate 900,000 tons of CO_2 compared to a gas powered 200MW power plants [32].

This technology will be suitable or villages at the core northern region in Nigeria. Application of solar chimney to interior villages in states like Borno, Yobe, Jigawa, Katsina, Zamfara, Sokoto and ome few other desert prone region states in Nigeria will enhance a better living for the people of the community and also increase the accessibility of rural areas to electricity.

Galadi *($13^0\ 03^{/}\ 24.\ 64^{//}N,\ 6^0\ 25^{/}\ 34.\ 94^{//}E$)* is a small village under Shinkafi Local Government area of Zamfara state in Nigeria, this village has an estimated population of 5000 people and it is dominated by a northern tribe called Hausa in Nigeria. This power supply in this village is next to zero in that it only has erected electric poles but no power supply. The situation in Wuya *($12^0\ 04^{/}\ 11.\ 54^{//}N,\ 6^0\ 05^{/}\ 48.\ 79^{//}E$)* is also similar to that of Galadi but in this village not power supply or electric poles. Wuya is located in Anka local government of Zamfara and has an estimated population of 5000. Both villages are about 3 hours drive from Gusau (Zamfara state capital). Kwanren-ganuwa is a village under Tsafe local government area of Zamfara state too. The main source of electricity in this village is personally owned small capacity fuel generators. The population size is similar to the two villages mentioned above. Below are some of the pictures taken during a visit to these places mentioned.

Application of solar chimney will be a great relief to the people of these communities and a 2MWsmall scale solar chimney power plant will be sufficient to power each of these villages both at peak load and base load. The use of manual labor such as volunteers from the villages will greatly reduce the cost of construction these power plant by 20% and the power plant may be so low in terms of cost of construction to have a payback period of 2-3years and this power plant can last for years if properly maintained. The low or no maintenance cost of this the solar technology also makes it very good for these areas because there won't be any need to always transport skilled personnel to the location of the power plants

5 CONCLUSION

Although no commercial solar chimney power plant is current available in the world especialy in developed countries due to its low efficiency compared to the expanse of land used but solar chimney power stations will make important contributions to the energy supplies in Nigeria especially the northern desert villages. Electircity has proven over the to be one major source of power that is indespensable to the human race. The cost of constructiong a solar power plants with manual labor may be almost the same cost with running electrical cables to villages that are 200km far away from the nearest source of electricity.

Finally, solar chimney is also very important for the future as other solar power technologies are too, because almost all other energy resources are limited, except the renewable energy and sun is the most abundant source of energy in the world presently. Solar chimney is a technology that is still yet to be fully exploited and researched. The low efficiency of this technology is also a major setback for this technology and this has reduced its commercial acceptability and utility in developed countries and this need to be worked on if this technology will be useful for the future.

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