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Techno-Economic and Environmental Impact Analysis of A Passive Solar Cooker for Application in Nigeria

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ABSTRACT

This paper presents the economic analysis and environmental evaluation of a passive solar cooking system for sustainable application in the developing countries. The newly developed cooker was evaluated according to the two standard figures of merits F_1 and F_2, through; Temperature stagnation and water boiling tests. Sample cooking tests were conducted indoors under simulated solar radiation. Comparative performance tests of a painted and non-painted cooking pot were also undertaken and the result shows the painted pot heat gains was 22% compared to the non-painted cooking pot. The economic and environmental benefits of the system includes, reducing the daily burning of fuel wood, which would reduce deforestation, environmental and other ecological degradations. Over a 3^{rd} of the world population relied on fuel wood and biomass for their daily cooking needs and daily fuel wood requirement per person is 1.3 kg, using the cooker once daily could bring an annual savings of 1,281.2 Million tons and 114.2 Million tons of fuel wood and CO_2 respectively.

KEY WORDS: *Stagnation, Comparative, Economic and Environmental benefits*

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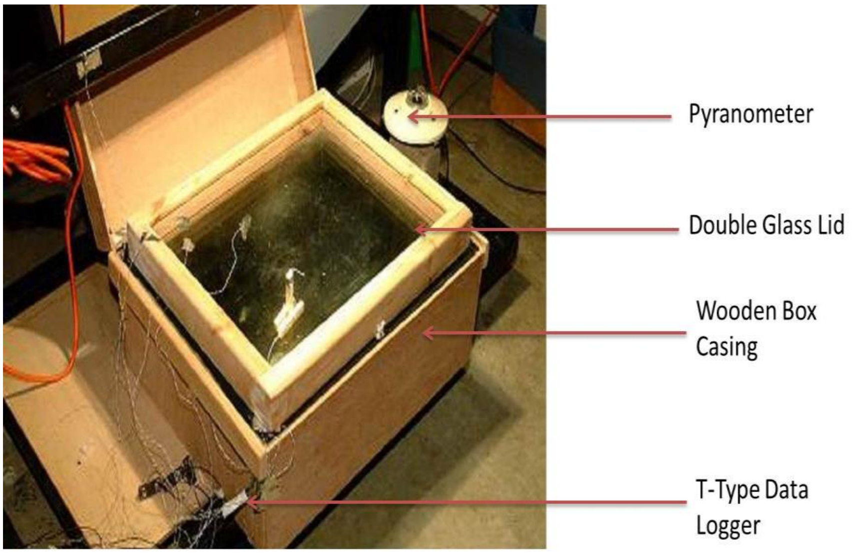
I. INTRODUCTION

40% of the world's poorest countries population use 70% of their fuel from fuel wood and charcoal inefficiently made from wood. In Tanzania, a country with 32 million people, over 90% of the country's energy comes from wood/charcoal about 40% fuel (Garg et al., 1985). Since the Industrial Revolution (around 1750), human activities have substantially added to the amount of heat-trapping greenhouse gases in the atmosphere. The burning of fossil fuels and biomass (living matter such as vegetation) has also resulted in emissions of aerosols that absorb and emit heat, and reflect light. The addition of greenhouse gases and aerosols are changing the composition of the atmosphere which in turn would influence the earth temperature, precipitation, storms and sea level (Subodh et al., 2005) .

According to the FAO, in the year 2010 as many as three billion people will have insufficient access to fuel wood to meet basic needs. Already this is the case in some areas. Contrary to findings in Tanzania, economically viable woodlot density required to make charcoal viable may be near zero in very impoverished countries. In Haiti even tree stumps and roots, the last remaining vegetation holding down the soil, are dug up to make charcoal. Every trace of a tree is removed to convert it to increasingly expensive charcoal, promulgating the ultimate 'scorched earth' policy (Subodh et al., 2005). In some coastal areas, mangroves are cut below water line to feed the charcoal kilns, weakening the trees and eventually killing them. Without mangroves, estuaries can fall into rapid decline, spreading ecological devastation (*Nandwani 2005*) two third of developing countries are in the midst of a fuel wood shortage. Approximately 2.4 billion people over one-third of all humanity and two-thirds of the developing world cook over biomass fuel wood, charcoal, dung and crop residues. Millions of people become sick each year from drinking contaminated water; Children are especially susceptible (Nandwawi 1996). Due to the increasing population in the developing countries, demand for both wood and agricultural land has risen to such an extent that there is now a net depletion of wood resources with some serious present and potential consequences such as soil erosion, food shortage, and fuel wood shortage. In addition to improving efficiencies of wood-based cooking devices and introducing other biomass-based fuels, the use of solar cookers is one way of reducing the demand for firewood (Schwarzer et.al, 2008).The rate at which our environment is being exposed to global warming, ozone layer depletion and dessert encroachment as the result of human interference cutting down trees for energy needs is alarming in the developing world. Averagely over 80% of energy consumption in the developing world relied on fuel wood and charcoal on a daily basis. Apart from the CO_2 released to the environment, the use of fuel wood is causing desertification and other ecological degradation which drastically affects the land fatality.

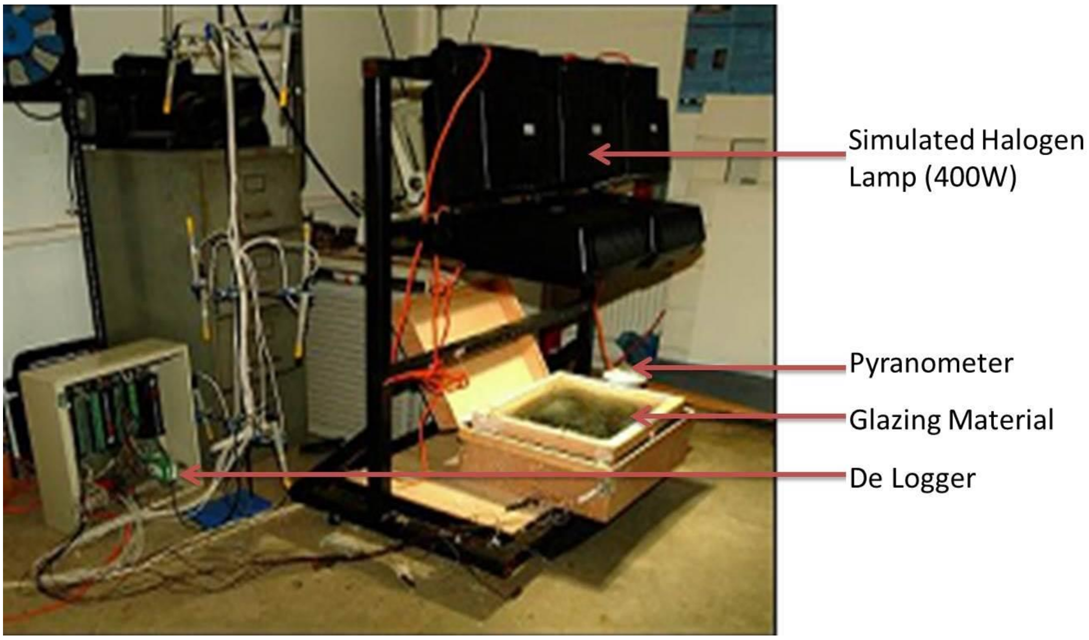
The solar cooking system : Simple box solar cooker was developed from recycle materials, the solar cooker was made up of 4 components as wooden box casing, metallic tray covered by, double glass lid and reflecting booster as presented Figure below

Figure 1: Developed passive solar cooking system



Test methodology : Indoor performance evaluation of the developed rectangular box solar cooker was conducted at Nottingham climate 52.96 N latitude. Simulated solar radiation made of couple of 400W halogen lamps was employed. CM11 Pyrometer recording instrument and T-type thermocouples were systematically connected to De-logger-

Figure 2 Experimental rig on indoor set up position



Experimental rig on indoor set up position plus Data taker employed to monitor various temperature profiles and the radiation during the tests in progress. These experimental set-ups of the test rig and instrumentations are presented in Figure 2.The recorded parameters include ambient, plate, top glazing, and bottom glazing and insulation temperatures. The system evaluation tests were conducted according to the two standards figure of merits F_1 and F_2 respectively. Sample cooking tests were carried out using the simulated halogen lamp

Stagnation temperature test : The first test conducted is the temperature stagnation test, this evaluate the newly developed rectangular solar cooking system in line with the box cookers. (Mullick et al., 1996) defined First figure of merit (F_1) for Box type solar cookers evaluation as; the ratio of optical efficiency $F'_{\eta o}$ to overall heat loss coefficient F'_{UL} . This is represented as;

$$F_1 = \frac{F'_{\eta o}}{F'_{UL}} = \frac{T_p - T_a}{H} \text{ ------ (1)}$$

T_a ambient temperature, Tp pot temperature and H is Solar radiation.

The first figure of merit F_1 of the solar cooker can be evaluated from equation (1) as;

$$F_1 = \frac{T_p - T_a}{H} = \frac{105 - 22}{600} = 0.14 \textbf{ --- (2)}$$

Air stagnation test coupled with the above equation, provides a general guide for evaluating solar cookers in which a minimum of 0.12 is required for high thermal effectiveness of the system while 0.11 is not acceptable (Garg et al., 1986).Secondly the Second figure of merit (F_2) is another formula for evaluating box type solar cookers through water boiling tests. The second figure of merit F_2 is related to F_1 with other parameters and is given in the following Equations (3) and (4)

$$F_2 = F'_{\eta o} C_R = \frac{F_1 (MC)_w}{A_\tau} \ln \left[\frac{1 - \frac{1}{F_1}\left(\frac{T_{w1} - T_a}{H}\right)}{1 - \frac{1}{F_1}\left(\frac{T_{w2} - T_a}{H}\right)} \right] (3)$$

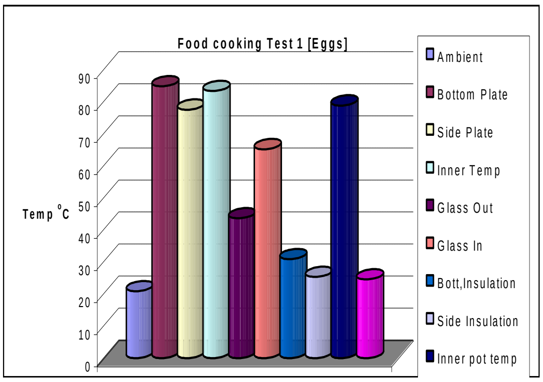
$$F'_{\eta o} = \frac{F_1 (MC)_w}{C_R A_\tau} \ln \left[\frac{1 - \frac{1}{F_1}\left(\frac{T_{w1} - T_a}{H}\right)}{1 - \frac{1}{F_1}\left(\frac{T_{w2} - T_a}{H}\right)} \right] (4)$$

Water-boiling tests : In the F2 water boiling test, one litre of water is used to evaluate the cooker performance, the test results shows the solar cooker has satisfied the 2 figures of merits. Using a radiation level of $600W/m^2$ the following temperatures were recorded 110^oC and 86^oC for bottom plate and inner pot (water) temperatures respectively. 3 parameters were most important in the stagnation test namely; solar collector temperatures, glazing and insulation. The highest recorded temperature was the bottom plate 110^oC then followed by the inner plate and side plate temperatures 75^oC and 74^oC respectively, while the inner and outer glass temperatures were 62^oC and 42^oC. The bottom, side and inner insulations were recorded as 32^oC, 25^oC and 23^oC. This shows the most heat loss was at the bottom of the cooker. Therefore additional insulation at the bottom would raise the efficiency of the cooker by reducing the bottom heat loss.

Comparative painted / unpainted cooking pots test : Many researchers argue on which material is best used for solar cooking, some use aluminium foils while others use Perspex. Water boiling test was conducted between painted and unpainted pots. In these tests one litre of water was used to evaluate the performances of the two cooking pots. Temperatures of 83^oC and 101^oC for the unpainted cooking pot temperatures and 91 ^0C to 108 ^0C plate temperatures for the painted cooking pots was attained respectively the unpainted pot has shown a temperature difference of 18^oC.The comparative test has shown a better performance on the painted pot over the unpainted pot. This justifies the theory of using black body on both the collector tray surfaces and the cooking pot. Though still aluminium foils are still used instead of the mat black paint, but this test has shown better performance of the painted over the unpainted pot as other colour reflects while black absorbs.

Cooking performances tests : Two sets of cooking tests were carried out, some eggs and parboil long grain rice were cooked under simulated solar radiation.

Figure 3: Solar cooking evaluative test



A maximum temperature of 80°C was recorded in the pot for the eggs cooking this and other parameters are presented in Figure 3

Rice cooking : 300 grams of American parboiled long grain rice adequate for 3-4 adults was cooked under 3 hours using a simulated solar radiation of 600W/m^2

II. RESULTS AND DISCUSSION

From the results shown the developed system has passed the F_1 and F_2 standards of merits performances tests. Both Stagnation temperatures, Water boiling and cooking tests were conducted using simulated radiation of 600 W/m^2, a bottom plate temperature of 105°C was recorded from the box solar cooker. The estimated average daily fuel wood requirement per person in the developing world is 1.3 Kg; this amount of fuel wood is only for cooking and water heating. This has shown the amount of wood consumed on daily basis the wood burning apart from the associated health hazard (passive smoking) it emits huge CO_2 to the environment. Literature has shown about 3 billion people are in need of fuel wood in the world, therefore introducing a solar cooker to 2.7 billion people would bring a dramatic economic and environmental savings, the daily, monthly and annual fuel wood consumptions are shown. Single solar cooking can adequately cook for 5 people at a time. Using the solar cooking option would bring tremendous benefits in the developing world environmentally, economically and otherwise. Using a single solar cooker 3 times a day would save 2372.5 Kg of fuel wood annually.

Table 1:Fuel wood consumption in the developing world

period	Co_2/person	Family of 5	2.7 billion people
Daily	1.3 Kg	6.5 kg	35.1 Billions kg
Monthly	39Kg	195Kg	105.3 Billions Kg
Annually	474.5 Kg	2372.5Kg	1281.2 Billions Kg

CO_2 savings : CO_2 is one of the greenhouse gases responsible of causing global warming, which results in sea-rise, desertification, rainfall shortages, and danger of infrared radiation from the ultraviolet rays etc. The recent catastrophes of; Katrina, Tsunami and Bangladesh storm are living witnesses before us. For burning one kilogram of fuel wood 0.27 kg of CO_2 is released to the environment. Therefore the CO_2 released for burning 1,281.2 Million tons of fuel wood is 345.91 Billion Kg see Table 2.

Table : 2 CO_2 released to the environment from fuel wood

period	Co_2/person	Family of 5	2.7 billion people
Daily	0.351 Kg	1.755 kg	0.9477 B kg
Monthly	10.53Kg	52.65Kg	28.43 B Kg
Annually	128.1 Kg	640.58Kg	345.91 B Kg

When the cooker is used at least once a day the CO_2 savings would be 33, 33 %, The CO_2 savings would = 345.911* 0.33 = 114.15 Billion kg. Therefore for using a single solar cooker once a day, 640 kg of CO_2 would be saved annually.

Economics analysis : Solar systems are capital intensive. The cost of purchasing and installing a solar cooking system is high in comparison to the conventional system it replaces. But the conventional system is energy intensive, that is, the annual energy costs are higher than an equivalent solar system. Purchasers of solar systems expect the resulting fuel savings eventually to pay for the system and save on the cost of future energy needs.
Solar energy is a primary source of energy for our planet. Its increased utilisation would result in all-round benefit both in maintaining sustainability of the environment and economic gain. Further to its environmental benefits, using the solar cooker would save a lot of time and money since the energy source is free and it is easy to operate. The re-introduction of solar cookers as an alternative renewable energy source would go a long way in energy savings and conserving our forests decreasing deforestation.

System costs analysis : In the developing world - Nigeria for example - a family of five in [which is the design capacity of the developed solar cooker], requires a fuel wood of = £0.25p daily the estimated daily recurring expenses on fuel wood is presented below.

Table 3 of system cost analysis

Period	Amount/person	Fuel wood/person
Daily	25 p	1.3kg
Weekly	£ 1.75p	9.1 kg
Monthly	£ 7.50p	39kg
Annually	£ 90.00	£ 474.5 kg
5 Years	£ 450.00	2372.5kg
10 Years	£ 900.00	4745 kg

The rectangular box type solar cooker was constructed out of recyclable available materials, and its conservative estimate is to cost between £20.00 to £30.00 The system is mostly constructed from available materials, therefore mass production and vigorous orientation about its economic, environmental and social benefits would further reduce the cost of the viable renewable efficient solar cooker.

Payback period = Unit cost of the cooker / amount saved (per month).

Table 4: system payback period

Cooking	**System Cost**	**Monthly savings**	**Payback period**
3 meals a day	**£ 30.00**	**£ 7.50**	4 months
2 meals a day	**£** 30.00	**£ 5.00**	6 month
1 meal a day	**£ 30.00**	**£ 2.50**	12 months

When the solar cooker is used for three meals, the payback period is only four month and Using the solar cooker twice a day, the solar cooker's payback period would be 6 month When the system is used once a day its payback period would take a complete year and the system is expected to last for 10 years. Solar cooking system were introduced and monitored in refugee camps in Somalia and some other parts of East Africa. The average use of the cookers were 25% and 75% for single meal and double meal cooking respectively and over 40% reduction of fuel consumption was recorded (Mullick et al.,1996) .Therefore by using solar cooker, the energy saving per person on an annual basis could drastically reduce cooking fuel consumptions down to 60%. Coking trials of the developed solar cooker were conducted; Rice vegetables eggs were perfectly done under the simulated radiation. The solar cooker popularization especially in the developing world would go a long way in reducing the poverty level increase the income of the common people from the savings the fuel wood could be used in other essentials needs and saving the ecosystems, animal dung would instead be used as fertiliser aiding increase agricultural production and finally reducing CO_2 to the environment

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