THERMAL PERFORMANCE EVALUATIONS, ENERGY SAVINGS AND PAYBACK PERIODS OF A BOX-TYPE SOLAR COOKER IN IBADAN, NIGERIA

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Abstract: *This work presents the development, evaluation and some economic analysis of a box-type solar cooker in the tropical climate of Ibadan. The performance evaluation included the determination of the first and second figure of merits (F_1 and F_2), the cooking power and the standardised cooking power. Based on the number of solar meals that can be cooked in a year, economic analyses of the solar cooker were carried out. Some financial parameters were estimated for the solar cooker which includes Cumulative Cash Flow (CCF), Net Present Value (NPV), Simple Payback Period (SPP), and Discounted Payback Period (DPP) with respect to other cooking fuels viz; Liquefied Petroleum Gas (LPG), Kerosene, Charcoal, Firewood and Electricity. The annual energy savings and Carbon dioxide (CO_2) mitigation as a result of using the solar cooker were also estimated. A maximum stagnation temperature of 126^oC was achieved in the solar cooker and the water boiling test took 120 minutes. The F_1 and F_2 values ranged from 0.11 – 0.13 and 0.24 – 0.30 respectively. Maximum cooking power and standardised cooking power of 92.4 W and 85.6 W respectively were achieved. The CCF of the solar cooker ranged from $140.34 to $382.39 while NPV ranged from $89.09 to $348.33 with cooking using electricity yielding the least and cooking using LPG yielding the highest. The LPG has the shortest SPP and DPP of 7 months while electricity has the longest SPP and DPP of 18 months and 20 months respectively. Annual energy savings ranged from 1728 MJ to 18922.6 MJ. Annual CO_2 mitigation was estimated to be between 164.8 kg and 2119.3 kg.*

Keywords: Figure of merit, Cooking powers, Economic analysis, Energy savings

1. INTRODUCTION

In Nigeria, the energy sources used for cooking includes fossil fuels (Kerosene, Liquefied Petroleum Gas, Biomass fuels/Fuel wood and Coal) and Electricity. Each of these has one major challenge or the other. The non-functional or low capacity production of our refineries and the problem of vandalization of our oil pipelines have made the country a net importer of refined petroleum fuels which leads to a hike in their prices, hence making them unaffordable by the people, majority of whom are low income earners. Again when they are available, the supply favours the urban areas than the rural areas where 70% of the country's population live.

Electricity production in Nigeria is more from thermal generator that make use of gas. The problem of vandalization of gas pipelines has reduced production from these sources, causing very low supply. Apart from this, about 30 million people are not connected at all and the low supply available is also in favour of the urban areas. For example, only 40% of the population is connected to the national grid with 90% of rural areas having unreliable or no electricity at all. This leaves a majority of the people with the use of biomass fuel which apart from being available also attracts low cost. The reliance on Fuel wood for the supply of energy for cooking has deforestation as its attendant problem, which contributes also to desertification. The equivalent of 410,000 hectares of forested land is being lost annually [1], [2]. Another major concern with the use of burning biomass is indoor air pollution from open fire usually in houses without chimneys leading to respiratory diseases and premature deaths. Furthermore, constant search for Fuel wood represents burden for women and children particularly in rural areas.

In an attempt to address all these aforementioned problems, there is a dire need to search for an alternative energy source which if available, will be affordable; address the health issue and reduce the pressure on biomass resources. This makes solar energy through the use of solar cookers a viable option. Nigeria receives 16.7 x 10^{15} kJ of solar energy each clear day. Estimates have revealed that using one percent of the available land area (983.2 x 10^6 m^2) for 180 clear days in the year operating at 5% conversion efficiency, the equivalent of 15.0 x 10^{14} kJ of useful energy would be available annually to the country, this figure is equivalent to the national fossil fuel production with the dual advantage of renewability and environmental protection [3].

The use and availability of solar cookers in Nigeria has been restricted to research institutions [4] hence, the need for the effective dissemination of the technology to the teeming populace. For this to take place, apart from having to convince people on its functionality, there will be the need to also prove its economic viability. Hence, the objective of this work was to evaluate the thermal performance and economic viability of a box-type solar cooker in Ibadan metropolis, Oyo State, Nigeria.

2. METHODOLOGY

A family size solar box cooker capable of cooking meals for 4 to 5 persons was constructed. The constructed cooker has an aperture area of 0.25m^2. The boxes were made of plywood while coconut coir was used as insulating material. Aluminium foil was as the reflector.

2.1 Performance Evaluation

Stagnation temperature test was carried out for the solar box cooker and first figure of merit (F_1) was determined using equation 1. Water heating test was also carried out and the time taken to boil a known mass of water was recorded. The second figure of merit (F_2) was also determined using equation 2. Cooking power was determined using equation 3 at intervals and was corrected to a standard of 700W/m^2 using equation 4 [5]. The standardized cooking power was plotted against the temperature difference for each interval. A quantity of food sufficient to feed 5 persons was cooked on each of the cookers, recording the time spent and the energy consumed [6].

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

$$F_2 = \frac{F_1 \; MC \;\; w}{A\Delta t} \ln \frac{1-\frac{1}{F_1} \; \frac{T_{w1}-T_a}{H}}{1-\frac{1}{F_1} \; \frac{T_{w2}-T_a}{H}} \quad (2)$$

$$P_i = \frac{T_2-T_1 \quad MC \;\; w}{600} \quad (3)$$

$$P_s = P_i \; \frac{700}{H_i} \quad (4)$$

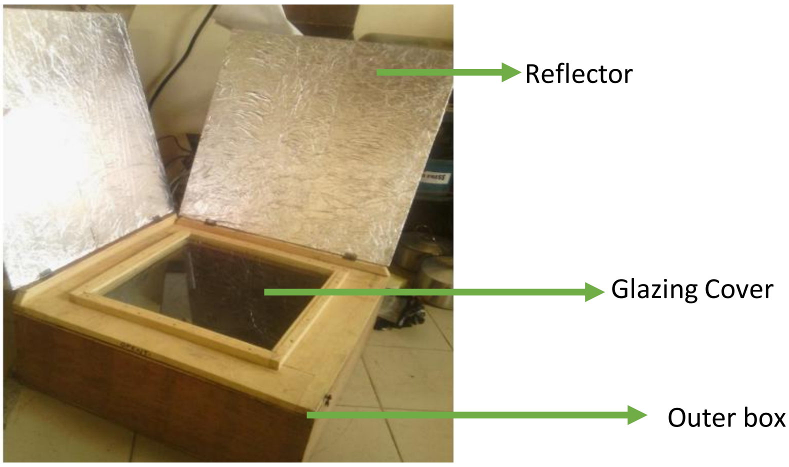

Figure 1: Solar box cooker

2.2 Economic Analysis

The costs of operating each of the cookers were estimated per annum for all the cookers and compared with the cost of combined usage of solar cooker with the existing cooker. Some of the financial parameters used by [7] were adopted in the financial evaluation of the solar box cooker. Other parameters such as Cumulative Cash flow (*CCF*) and Simple Payback Period (*SPP*) were also estimated.

The cost of operating each of the fuel cookers was estimated per meal for a representative meal cooked on each of the cookers. The operating C_{oi} was taken as the addition of the running cost and maintenance costs. Since solar box cooker has little operating cost i.e. its maintenance cost; the saving per meal compared with other cookers is given by equation 5. This was estimated per annum considering the average number of days with sufficient insolation in a year. The solar cooker usage was taken as a capital project investment with the cost of the solar cooker C_{cs} as the capital investment and the annual savings P_i with respect to cooker *i* utilization as the cash inflow; the cumulated cash flow *CCF* was calculated using equation 6.

$$S_i = C_{Oi} - C_{OS} \quad (5)$$

$$CCF = -C_{CS} + NP_i \quad (6)$$

Where *N* is the useful life of the solar cooker (years). The simple payback period *SPB* was calculated using equation 7.

$$SPB = \frac{C_{CS}}{P_i} \quad (7)$$

Considering the time value of money with interest rate *r*, Net Present Value, *NPV*, of the project is given by equation 8.

$$NPV = -C_{CS} + \sum_{y=1}^{N} \frac{P_i}{(1+r)^y} \quad (8)$$

The discounted payback period DPB was given by equation 9.

$$DPB = \frac{\ln\left(\frac{1}{1-rSPB}\right)}{\ln(1+r)} \quad (9)$$

2.3 Annual Energy Savings

The energy savings which accrued to solar cooker usage is the energy saved from the usage of the solar box cooker compared with the existing cookers. The mass of fuel consumed in cooking each meal using the existing cooker is given by equation 10.

$$m_{ri} = m_i t_{ri} \quad (10)$$

The annual energy savings is given by equation 11.

$$E_i = m_{si} h_i \quad (11)$$

With respect to electric cooker, annual energy savings E_e is given by 12.

$$E_e = cooker\ wattage\ \times\ t_r n_y \quad (12)$$

2.4 CO_2 Mitigation

The environmental pollution mitigated annually (via reduction in CO_2 release) as a result of using the solar box cooker depends on the amount of CO_2 prevented from being released from each of the cooking fuels. The annual carbon dioxide mitigation is given as follow in equation 13.

$$Annual\ CO_2\ mitigation = E_i \times fuel\ specific\ CO_2\ production \quad (13)$$

3. RESULTS AND DISCUSSION

3.1 Performance of Solar Box Cooker and Economic Analysis

The stagnation temperature of 126.0^{o}C was obtained as the maximum value using the solar cooker. The temperature profile recorded during the stagnation test is shown in figure 2. This same trend was also reported by [8]. The first figure of merit F_1 has range of 0.24 to 0.30 with maximum cooking power of 97.65W. Similar findings were reported by [9] and [10]. A maximum standardized cooking power of 85.56W was obtained.

The capital cost expended in constructing the solar box cooker was $56.25. The costs of these cookers are less than one third of some commercially available model. Similar findings were reported by [11]. The weather data analysis in Ibadan showed than an average of 300 meals can be cooked in a year. The financial parameters obtained for the solar box cooker used as supplementary with the existing cooking fuels are given in Table 1. The NPV of the savings generated as compared to each cooker usage is substantial. This is quite encouraging at a time of economic instability, especially to the low income families. The returns from solar box cooker can be ploughed into other uses to help improve the standard of living of such families. The solar box cooker can be encouraged to supplement the conventional cooking methods. If invested in, the solar box cooker has a short payback period. If a loan is taken to invest in the solar box cooker, the loan can be repaid in a short time. This is estimated based on the assumption that the cash inflow is uniform throughout the months of the year. However, this may not be so because the revenue is dependent on seasonal variation of the weather condition within the year. It is based on the assumption that the solar box cooker is used instead of any of the existing cookers at every available period of sufficient solar insolation. If utilized, solar box cooker will help strengthen the economy of families in Ibadan city and other locations where there is abundant sunshine.

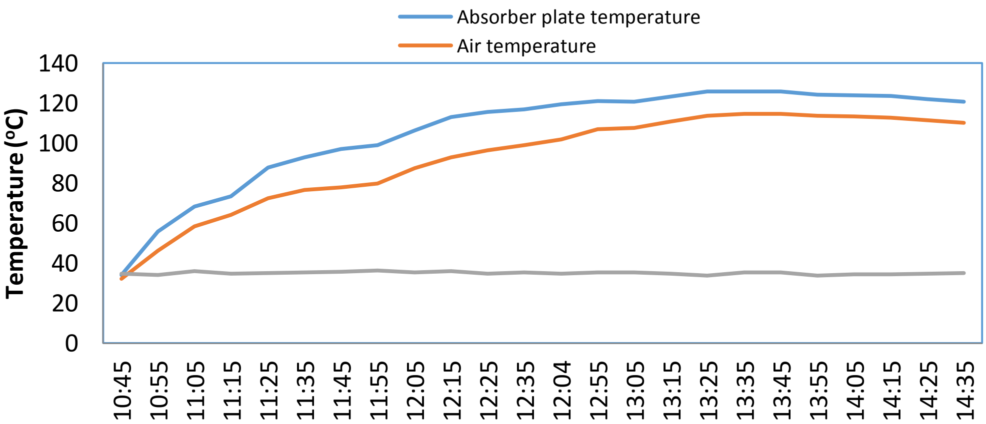

Figure 2: Temperature profile during stagnation test

2.2 Annual Energy Saved

The estimated annual energy saving of the solar box cooker with respect to each of the cooking fuels is shown in Table 2. A huge amount of energy could be saved by usage of solar box cooker in each family. When cooking is done with kerosene or fuel wood, about 80 – 90% of energy is wasted to the environment [12]. The solar box cooker prevents such wastage. This shows a great prospect for country like Nigeria and other developing countries who are yet to meet their energy demands; especially in electricity supply. The energy saved from electricity consumption could be diverted to other use.

Table 1: Estimated Financial Parameters Using Solar Box Cooker as a Supplementary to Kerosene, Charcoal and Fuel Wood Cookers.

COOKER SUPPLEMENTED	ANNUAL SAVINGS ($)	CCF ($)	NPV ($)	SPB (Months)	DPB (Months)
LPG	109.47	491.09	348.33	7	7
Kerosene	58.86	238.13	161.35	12	13
Charcoal	72.15	304.48	210.40	10	11
Fuelwoood	77.87	334.57	231.55	9	10
Electricity	39.33	140.38	89.10	18	20

2.3 Carbon Dioxide Mitigation

The CO_2 mitigation using solar box cooker annually is shown in Table 2. A huge amount of CO_2 will be prevented from being released to the atmosphere by using the solar box cooker. Firewood burning releases the highest amount of CO_2 to the atmosphere when used for cooking compared with kerosene and charcoal. The attendant deforestation occurring with usage of wood as fuel for cooking is a strong reason for replacement of wood with solar box cooker.

Table 2: Estimated Annual Energy Savings and CO_2 Mitigation Using Solar Box Cooker

COOKING FUEL	ANNUAL ENERGY SAVINGS (*MJ*)	ANNUAL CO_2 MITIGATION (Kg)
LPG	3963.72	250.11
Kerosene	2291.52	164.76
Charcoal	8530.41	955.41
Fuelwood	18922.60	2119.33
Electricity	1728.00	233.42

CONCLUSION

The results from this study show the performance and economic analysis of a box-type solar cooker. The first and second figure of merits (F_1 and F_2) had a range of 0.11 – 0.13 and 0.24 – 0.30 respectively. The cooking power was 92.4W. A maximum stagnation temperature of 126^{o}C was obtained in the solar cooker and the water boiling test took 120 minutes. Standardised cooking power of 85.6 W was recorded. The CCF of the solar cooker ranged from $140.34 to $382.39 while NPV ranged from $89.09 to $348.33. Cooking with electricity yields the least and cooking with kerosene yields the highest. The kerosene has the shortest SPP and DPP of 7 months while electricity has the longest SPP and DPP of 18 months and 20 months respectively. Annual energy savings ranged from 1728 MJ to 18922.6 MJ. Annual CO_2 mitigation was estimated to be between 164.8 kg and 2119.3 kg. Solar box cooker has tremendous benefits ranging from cost saving to energy saving. It is therefore recommended that solar cookers are good alternative for cooking in the quest to make human activities go greener.

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LIST OF NOTATIONS

i	notation to represent fuel types (g for LPG; k for Kerosene; c for Charcoal; w for Fuelwood and e for Electricity
m_{ri}	Mass of fuel consumed by cooker in cooking representative meal *i* (Kg)
m_{si}	Mass of fuel saved in the year by using fuel *i*
t_{ri}	Time spent in cooking representative meal using fuel *i*
p_i	Purchase price of fuel i ($)
C_{ci}	Capital cost of cooker using fuel *i*
C_i	Cost of cooking the representative meal using fuel *i*
C_{im}	Cost of ignition material per meal ($)
C_{ri}	Running cost of cooker using fuel i ($)
C_{oi}	Operating cost of cooker using fuel i ($)
C_{os}	Operating cost of the solar cooker ($)
C_{mi}	Maintenance cost of cooker using fuel f ($)
S_i	Savings per meal on cooker using fuel f ($)
n_y	Number of meals that can be cooked in the year with Solar Box Cooker
P_i	Annual savings of cooker using fuel ($)
CCF	Cumulative Cash flow ($)
C_{cs}	Capital cost of solar cooker ($)
N	Number of useful years of solar box cooker
SPB	Simple Payback period (months or years)
NPV	Net Present value ($)
DPB	Discounted Payback period (months or years)
E_i	Annual Energy savings by using Cooker *i*
h_i	the specific heating value of fuel *i*