Evaluating Biomass Cook Stove Performance and Harnessing Waste Heat for Power Generation Using Thermoelectric Technology

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Abstract: The utilization of biomass cook stove is cautiously improving, particularly, in the hinterland of Nigeria. Considering this fact, a biomass stove was produced and evaluated for quality performance using fuels such as briquette and lump charcoal. The stove was fabricated using galvanized steel and lagged to enhance the effect and safety. In middle of this, reasonable amount of excess heat was harvested for conversion into electrical energy using a procedure called the seek beck effect. The behaviour of the cook stove was assessed in terms of thermal efficiency and measured during the time of cooking. A thermoelectric module (TEG 2- 126LDT) possessing distinct cold and hot sides was wedged alongside an aluminum heat sink after which was screwed to body of the stove. Two experiments employing two and three thermoelectric modules were conducted to establish how best to produce electricity while using the cook stove. The stove exhibited thermal efficiencies of 75% and 60.5% for briquette coal and the lump coal respectively. These results demonstrated satisfactory thermal efficiency, despite the fact that briquette coal showed superior performance. The power generated from heat to electricity conversion were 5.45W and 7.70 W. These results suggest that, by having more modules sandwiched and combing it with an efficient water cooling method, higher electrical power can be generated.

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I. INTRODUCTION

In Africa, over and above 82% of the people rely on solid biomass fuels to meet their foremost cooking needs, still only 11% utilize clean cook stoves and fuels [1]. Wood fuel is quite common, not just in rural communities but also amidst urban residents in the course of ceremonies and special occasions. Its acceptance originates from its inexpensiveness and availability in contrast to modern fuels like cooking gas or electricity. Nevertheless, large dependence on wood fuel has subjected us to dangers such as environmental troubles, extensive deforestation, habitat wrecking, climate changes, and increased exposure to natural disasters [2].

Over four decades ago, researchers reviewed biomass as a substitute due to its renewable nature, viability, abundance and possibility to lessen environmental effect. In addition, agricultural by products usually relinquished in the process of land preparation, planting, reaping, conveyance, and consumption provides appreciable unexploited material for energy generation [3].

Fuel and cooking are very important to our day to day living. In Nigeria, as a result of inflation, fossil fuels namely kerosene and cooking gas has been positioned off limit of a large number of families most especially in the rural and suburban areas. This rising inaccessibility emphasizes the desperate desire to reconnoiter other alternative renewable and worthwhile energy for domestic use. In view of the fact that fossil fuels are non-renewable; awareness need to pivot towards other sustainable energy sources such as biomass [4].

A key example of an alternative energy source is known as briquette. These compressed blocks of inflammable briquette are readily available, extremely economical, and user friendly. Biomass materials can be converted into fuel briquettes. Organic fibers when compressed brings about briquettes typically, with the help of a binder into solid forms which are then ignited to generate heat for cooking [5].

Solapure et al. [6] underscore the provocation of obtaining a blue flame an indicator of complete combustion in traditional cook stoves. Incomplete combustion in these stoves, due to the discharge of unwholesome gases, have contributed to higher respiratory illnesses and death.

This resulted into reinforced actions in producing biomass cook stoves with refined performance. A device called thermoelectric generator was used to harvest the heat during the time of cooking and then directly convert it into electricity.

Odesola and Kazeem [7] came up with an eco-friendly biomass cook stove created to meet cooking energy essentials using the biomass gasification method. The stove, was powered by charcoal, used in a forced draft mode and was lagged with fire clay to reduce heat losses. It obtained thermal efficiency which ranges from 52% to 61.4%, with a heat utilization rate of around 40.65%.

Sengar et al. [8] fabricated a funnel-shaped biomass cook stove, deploying teak and khakro wood branches as the major biomass fuels. The stove was assessed and juxtaposed with a traditional cooking system. The produced cook stove displayed thermal efficiency of 20.19%, power input of 17.76 kW, power rating of 3.55 kW, and fuel consumption rate of 4 kg/hr. In disparity to the traditional cooking set up which showed a thermal efficiency of below than 10% and a fuel consumption rate of around 8 kg/hr.

Champier et al. [9] designed a biomass-fired cook stove comprising of a thermoelectric module (TEG) to produce electricity for powering a fan and providing lighting. The blended fan enhanced the combustion rate by supplying enforced air to the stove. The research realized that the water-cooling method for the TEG was far better than air cooling, allowing the system to produce 6 W of electrical power while utilizing four thermoelectric modules.

Osmani et al. [10] fabricated an efficient open biomass stove and performed several experiments using biomass fuels. The results obtained goes to show that water-cooling method was way better in converting heat into electricity using a thermoelectric generator (TEG). It generated about 4.6 W of electrical power at a temperature difference of 138°C.

Ditthaphat [11] analyzed and remodeled a waste heat energy conversion tool using a (TEG) incorporated with LPG cook stove. During the experiment, four high-temperature thermoelectric modules were used and the system finally generated a power output of 107 W within a temperature difference of 278.5°C.

II. RESEARCH METHODOLGY

This section of the review defines the research methods, elemental principles of thermoelectric device, mathematical modeling, materials applied, and the experimental model and approach, which are introduced in the following subsections

➤ *Basic Principles of Thermoelectric Module*

A thermoelectric module is a circuit made up of thermoelectric substances that directly turns heat into electricity. It normally comprises of two unlike semiconductor materials: an n-type (negatively charged) and a p-type (positively charged), fixed at their ends. Whereby temperature difference occurs between the two junctions, direct current run through the circuit. As the difference in temperature increases across the thermoelectric generator (TEG) the electrical output power likewise rises, as illustrated in Figure 1 [12].
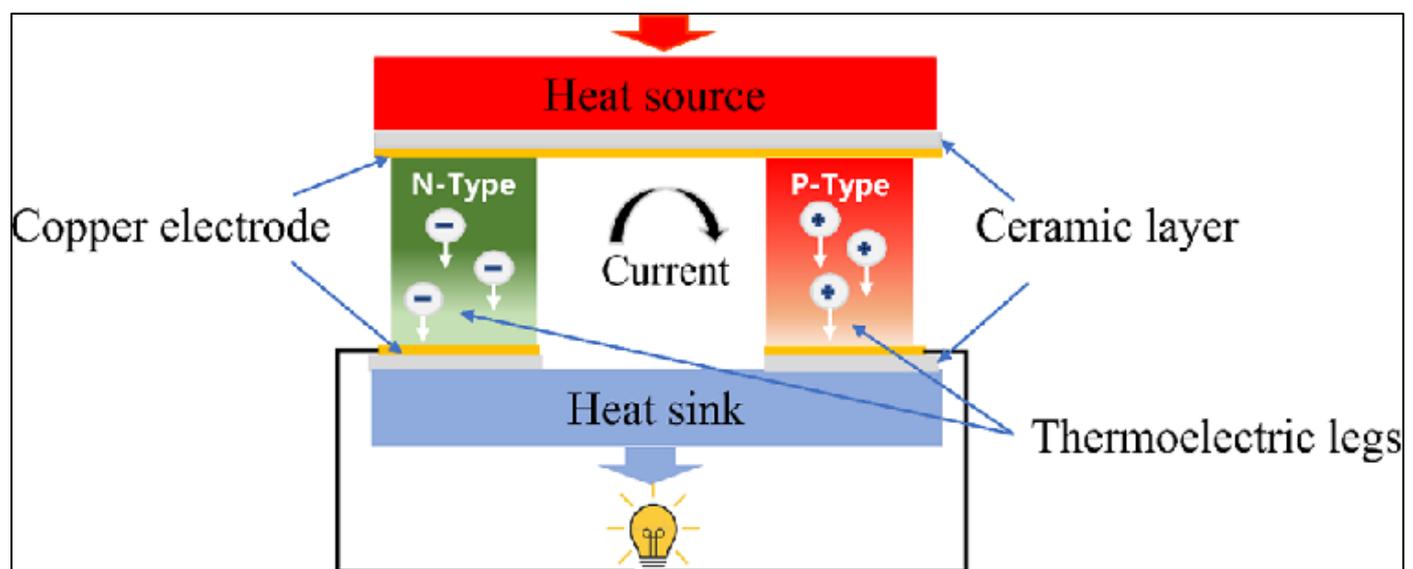

Fig 1 Thermoelectric Module Principle

➢ *Mathematical Models*

This module introduces the development of mathematical framework for the design of the biomass stove, concentrating on the analysis of fire power, thermal efficiency, specific fuel consumption, heat transfer, heat sink selection and electrical power output.

➢ *Design of Biomass Household Cook Stove for Power Generation*

• *Fire power (kW):*

This is the sum of thermal energy processed (kJ) per unit time (s). Mathematically it is presented as follows:

$$Fire\ power = \frac{mass\ of\ fuel\ burnt\ \times caloric\ valvue\ of\ fuel}{time\ taken\ for\ complete\ combustion\ of\ fuel}\ \frac{kJ}{s}\ or\ kW \quad [13]\ (1)$$

• *Energy Required (J):*

The energy essential to cook food per unit time is determined using the equation (2).

$$Q_n = \frac{M_f \times E_s}{t_s} \tag{2}$$

Where, Q_n is the energy needed to cook food, M_f is the mass of food to cooked (kg), E_s is the specific energy of food (kcal/kg), and t is the time required for cooking.

• *Fuel Consumption Rate (FCR):*

is the amount of fuel burnt per unit time and can be computed by the following relation shown in equation 3.

$$FCR\ (kg/h) = \frac{Q_n}{CV \times \cap} \tag{[13]\ (3)}$$

Where, cv is the calorific value of fuel (kcal/kg) and η is the efficiency of cook stove (%).

• *Stove Diameter (D):*

The specific gasification rate (SGR) of the biomass material, which span from 40 to 210 kg/m²·hr highlighted by Eshetu et al. [14] is a justification of the value of fuel exhausted per unit time. This correlation has been affirmed across various research on biomass stoves. Equation (4), as presented by Yohannes [15], is draw on to calculate the stove diameter.

$$D\ (mm) = \left[\frac{\left(\frac{4}{\pi}\right)FCR}{SGR}\right]^{0.5} \tag{4}$$

• *Stove Height (H):*

Nwakaire and Ugwuishiwu [16] described an equation for computing the height. The distance is measured from the base all through to the top of the stove burner using the Equation (5) where t is the working time for the stove ρ is the bulk density of fuel applied [8].

$$H = \left[\frac{SGR \times t}{\rho}\right] \tag{5}$$

• *Thermal efficiency:*

The thermal efficiency of a cooking stove to a great extent rely on the sucesss nature of heat transfer from the combustion point to the pot. In this research, it was rated during water boiling test using Equation 6 [16].

Where:
W_i = initial mass of water in the pot (kg)
W_f = Mass of final water in the pot (kg)
L_V = Latent heat of evaporation of water (2600 kJ/kg)
S_c = Specific heat capacity of water (4186 kJ/kg·°C)
T_i = Initial temperature of water (°C)
T_f = Final temperature of water (°C)
C_f = Calorific value of fuel
M_f = mass of fuel

$$\eta = \frac{S_c \times W_i(T_f - T_i) + L_V(W_i - W_f)}{M_f C_f} \tag{6}$$

• *Specific Fuel Consumption (SFC):*

This is defined as the quantity of fuel desired to produce a unit of output. Equation 7 from Ayo [13] was used for the calculation.

$$SFC = \frac{(M_i - M_{ff})}{W_i} \tag{7}$$

Where:
M_i = initial mass of fuel
M_{ff} = final mass of fuel

• *Heat Transfer from Combustion Chamber to the Walls of Stove:*

The radial conduction heat flow for a hollow cylinder is expressed using Fourier's law as shown in equation 8:

$$Q = -KA\frac{dt}{dx} \tag{8}$$

Where:
K is the thermal conductivity of the cylinder material;
A is the area of the walls of the cylinder heating chamber across which heat transfer occurs;
$\frac{dt}{dx}$ is the radial temperature gradient across the wall
Area through which the heat is transmitted as $A = 2\pi r L$
dr = Path length
L = Length of the stove burner

Therefore: $Q = -KA\frac{dt}{dr} = Q = -K.2\pi r L \frac{dt}{dr}$ per unit time or $Q.\frac{dr}{r} = -K.2\pi L dt$

Integrating both sides, we get:

$$Q\int_{r1}^{r2}\frac{dr}{r} = -K.2\pi L\int_{t_o}^{t_i}\frac{dt}{t}$$

$$Q[\ln r]_{r_1}^{r_2} = -K.2\pi L[t]_{t_i}^{t_o}$$

$$Q.\ln\frac{r_2}{r_1} = K.2\pi L(t_i - t_o)$$

Therefore:

$$Q = \frac{K.2\pi L(t_i - t_o)}{\ln\frac{r_2}{r_1}} = \frac{(t_i - t_o)}{\frac{\ln\frac{r_2}{r_1}}{2\pi KL}} \qquad (9)$$
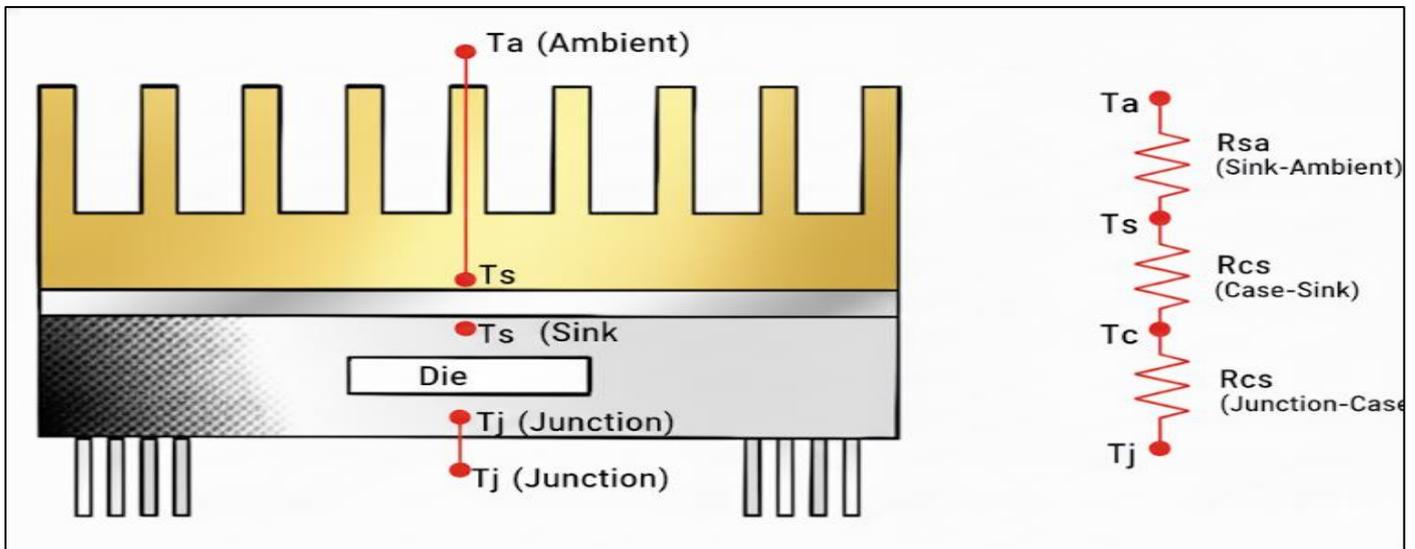

Fig 2 Heat Sink Assembly

The figure 2 above relates the various locations at which temperature readings could be taken across the heat sink. The equation 10 in accordance with Kamil et al. [17] was used to calculate the thermal resistance of junction to case (R_{JC}) of the heat sink.

$$R_{JC} = \frac{T_{JC}}{Q} = \frac{T_{Jmax} - T_C}{Q} \qquad (10)$$

Similarly, equation 11 was used to compute the thermal resistances of case to sink as required:

$$R_{cs} = \frac{T_{cs}}{Q} = \frac{T_c - T_s}{Q} \qquad (11)$$

Finally, equation 12 likewise was used to compute the thermal resistances of sink to ambient as needed:

$$R_{sa} = \frac{T_{sa}}{Q} = \frac{T_s - T_a}{Q} \qquad (12)$$

- *Heat Sink Selection:*
  The primary target of a heat sink is to remove heat from a source creating the heat. Heat sinks work through the mechanism of conductive and convection heat transfer:

- *Power:*
  This is the rate of doing electrical work or energy consumed per second. It reposes on on both voltage and current.

$$P = I \times V \qquad (13)$$

Where:
  P = Power
  I = current
  V = Voltage

➢ *Testing and Evaluation of Biomass Stove with TEG*

- *Water Boiling and Temperature Assessment Test*
  Figure 3 shows the experimental test of Water Boiling and Time spent cooking. A digital thermometer could also be seen used for temperature measurement. This procedure was conveyed in an open space in the morning and afternoon at ambient temperature of 29.8°C and 30.4°C respectively.

Fig. 3 Water Boiling and Temperature Measurement Test

- *Implementation of the modules*

   These key steps were carried out in the setting up of the thermoelectric module as shown in figure 4:

✓ The components were screwed up with slight increases. By the time the needed torque value was reached. We inspect again the torque and retighten.

✓ A stainless steel screw was used for the fastening. An Extender Block consisting of Aluminum or copper was used to produce a distance between the cold plate and hot heat sink (or water block) which permits for far better insulation.

✓ A heat passage was designed with heat pipes to aid movement of heat. It reduces the loss of waste heat from the top of the burner to the point where the TEG (thermoelectric generator) is installed. This would ensure faster heat delivery from the fireplace to the device.
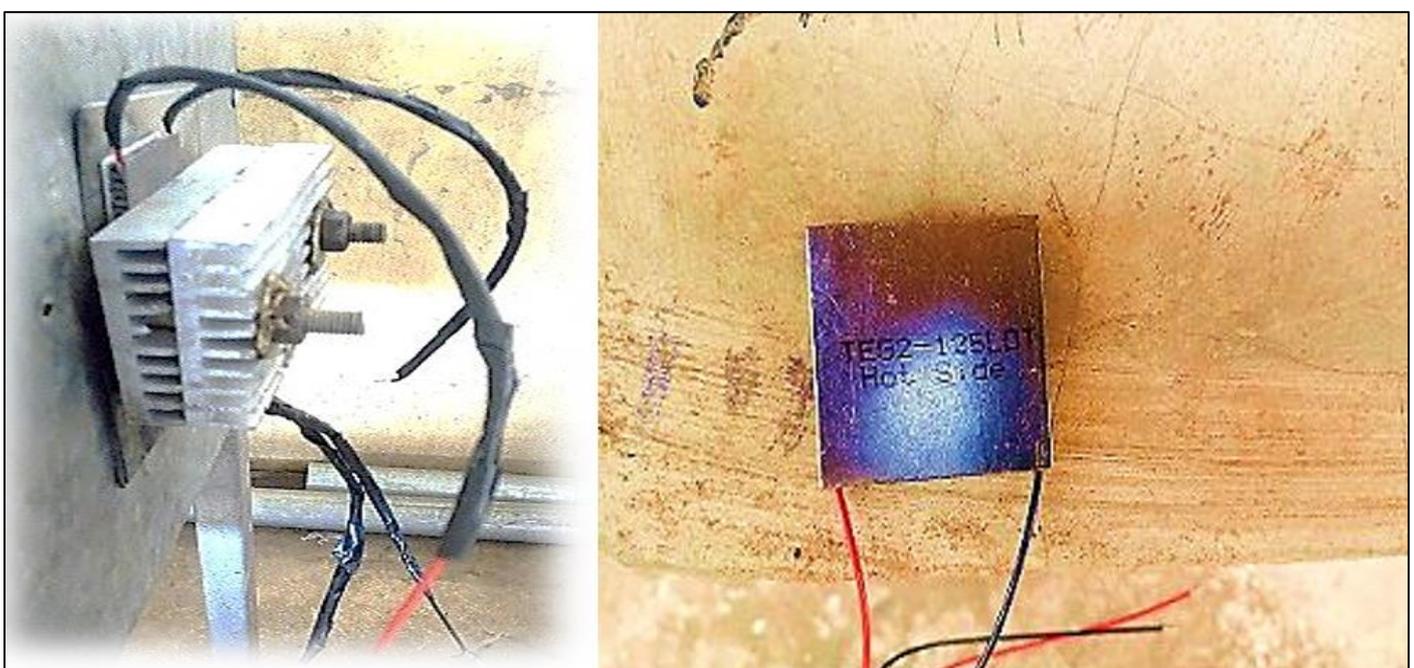

Fig 4 Set Up of the TEG with Heat Sink to Right Wall of the Stove

➢ *Experimental Procedure for The Generation of Electricity with the Aid of TEG*

The study analyzed the mode of action of heat conduction through a heat pipe deployed within the combustion chamber and attached to the stove wall. Data were collected after every three minutes for a duration of twenty-seven minutes using a digital thermometer. The spread of temperature across the hot and cold junctions of the module was observed. Figure 5 presents the model for assessing voltage and current while using the multimeter. The transport of waste heat took place through conduction, convection, and radiation, in that way establishing a temperature rise that enabled the generation of direct current.

Fig 5 Experimental Testing Showing Measurement of Heat Output

Microsoft Excel was used to calculate statistical metrics (mean, standard deviation, and standard error) for the measured temperature, voltage, current and power. Correlation analysis between two and three TEGs experimental results, as well as ANOVA, was done to evaluate the significance of the data.

III. RESULT AND DISCUSSION

➢ *Thermal Efficiency of the Cook Stove*

Figure 6 shows a contrast between two biomaterials used in accessing the cook stove efficiency. The inquiry indicated that both briquette and lump charcoal generated related functional heat gain of around 320 kJ, but briquette charcoal attained this with minimal fuel energy input (490 kJ vs. 730 kJ) and a higher thermal efficiency of (65.3% vs. 43.8%). This higher achievement is due to its uniform composition and controlled combustion. Thus, briquette charcoal is the more effective and viable fuel option.
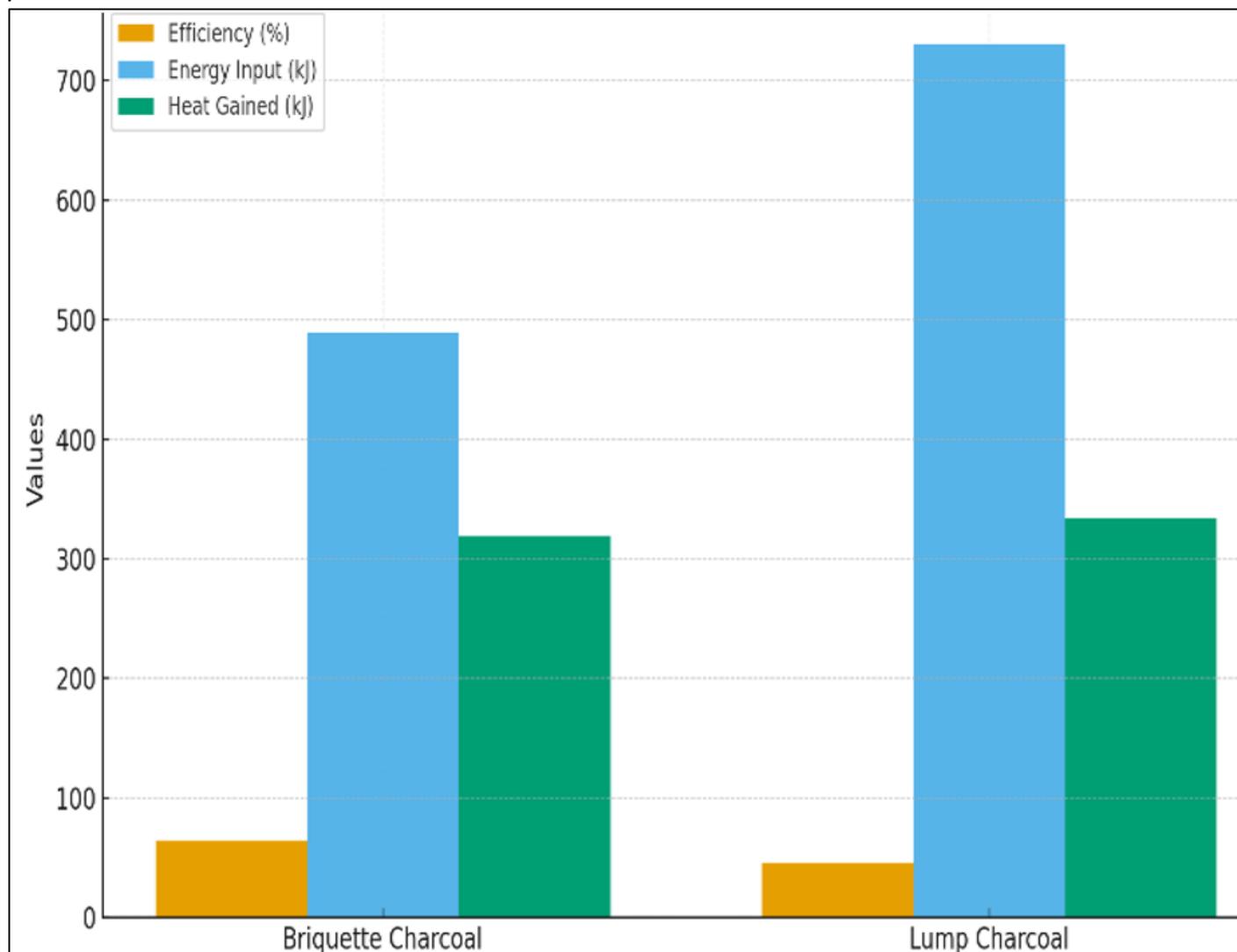
Fig 6 Comparison between Briquette and Lump charcoal

➤ *Energy Harvested from the Cook-stove*

Energy was recovered from the waste heat produced during the process of cooking with a biomass cook stove burner through the use of a thermoelectric generator (TEG) module.

Table 1 Temperatures from TEG modules

Time (minutes)	Three TEG			Two TEG		
	T (°C) hot	T (°C) cold	ΔT (°C)	T (°C) hot	T (°C) cold	ΔT (°C)
3	34.5	25.2	9.3	28.0	24.0	4.0
6	45.4	27.3	18.1	45.7	28.4	17.3
9	63.4	31.5	31.9	55.6	29.0	26.6
12	77.6	33.5	44.1	67.0	28.0	39.0
15	86.7	34.7	52.0	80.2	31.7	48.3
18	97.3	36.8	60.5	95.4	32.9	62.5
21	111.5	37.9	73.6	104.9	33.3	71.6
24	124.6	38.2	86.4	117.5	34.6	82.6
27	135.8	41.1	94.7	124.8	35.1	89.7
Mean	86.31	34.02	52.29	79.90	30.78	43.24
SD	34.69	5.25	29.55	33.38	3.67	31.30
MSE	11.56	1.75	9.85	11.13	1.22	10.43

Note: SD = Standard Deviation, MSE = Mean Standard Error

Table 1 describes the quantified hot-side and cold-side temperatures of the thermoelectric modules, likewise the resulting temperature differences (ΔT) for both the three-module and two-module configurations. With regards to the system, using three thermoelectric modules, the hot-side temperature averaged 86.31 ± 11.56 °C, with values spanning from 34.5 to 135.8 °C, while the cold side displayed mean temperature of 34.02 ± 1.75 °C. This brought about an average temperature difference of 52.29 ± 9.85 °C. In correlation, the two-module setup recorded an average hot-side temperature of 79.90 ± 11.13 °C (range: 28.0--124.8 °C), and a cold-side average of 30.78 ± 1.22 °C, resulting in a mean ΔT of 43.24 ± 10.43 °C.

The two configurations exhibited a continuous increase in hot- and cold-side temperatures over the period of the experiment. Although, the three-module system continually showed higher hot-side and lower cold-side values compared with the two-module. This propound that the use of three modules facilitated heat extraction, due to the wider cumulative heat contact space and higher general capacity for heat absorption. In addition, the broader temperature range observed for the three-TEG configuration (34.5 - 135.8 °C) stipulate a vigorous reaction to changes in the applied heat flux.

Table 2 Correlation Analysis Between Three and Two Tegs

Parameter	Three TEG	Two TEG
Mean ΔT (°C)	52.29	43.24
Standard Deviation (°C)	29.55	31.30
ANOVA F-Statistic	0.50	---
p-Value	0.489	---
Significance	Not Significant	---

Table 2 presents the correlation analysis between the Three TEG and Two TEG configurations. To determine whether the observed variation in performance between the two systems was statistically significant, a one-way Analysis of Variance (ANOVA) was performed on the temperature difference (ΔT) data. The analysis achieved an F-statistic of 0.50 and a p-value of 0.489, indicating no statistically significant difference between the mean ΔT values at the 95% confidence level. Nevertheless, the Three TEG configuration constantly recorded a higher average ΔT compared to the Two TEG system, insinuating a more fruitful heat utilization and a better potential for power generation under similar operating condition.

Table 3 Power Generation Using Two and Three Tegs

Time (mins)	Three TEG				Two TEG			
	ΔT (°C)	Voltage (V)	Current (I)	Power (W)	ΔT (°C)	Voltage (V)	Current (I)	Power (W)
3	9.3	0.96	0.19	0.18	4.0	0	0	0
6	18.1	5.02	0.27	1.35	17.3	3.01	0.17	0.51
9	31.9	5.28	0.42	2.21	26.6	5.01	0.29	1.45
12	44.1	5.92	0.57	3.37	39.0	5.40	0.40	2.16
15	52.0	6.53	0.63	4.11	48.3	5.50	0.55	3.02
18	60.5	6.98	0.71	4.95	62.5	6.17	0.58	3.57
21	73.6	7.25	0.74	5.36	71.6	7.05	0.61	4.30
24	86.4	7.41	0.89	6.59	82.6	7.50	0.65	4.87
27	94.7	7.86	0.98	7.70	89.7	7.57	0.72	5.45
Mean	52.29	5.91	0.60	3.98	43.24	5.25	0.44	2.81
SD	29.55	2.09	0.27	2.46	31.30	2.43	0.24	1.92
MSE	9.85	0.70	0.08	0.82	9.94	0.81	0.08	0.64

Table 3 indicates that the experimentally measured voltage, current, and power realized from the stove's waste heat as a function of the difference in temperature. Voltage measurements were obtained using a digital multimeter. The mean voltages for the three- and two-thermoelectric module arrangements were 5.91 ± 0.70 V and 5.25 ± 0.81 V,

respectively. The corresponding average currents were 0.60 ± 0.08 A and 0.44 ± 0.08 A, while the approximate powers were 3.98 ± 0.82 W and 2.81 ± 0.64 W, respectively. By and large, the three-module configuration did better than the two-module setup across all electrical parameters, a result accredited to its larger temperature differential.
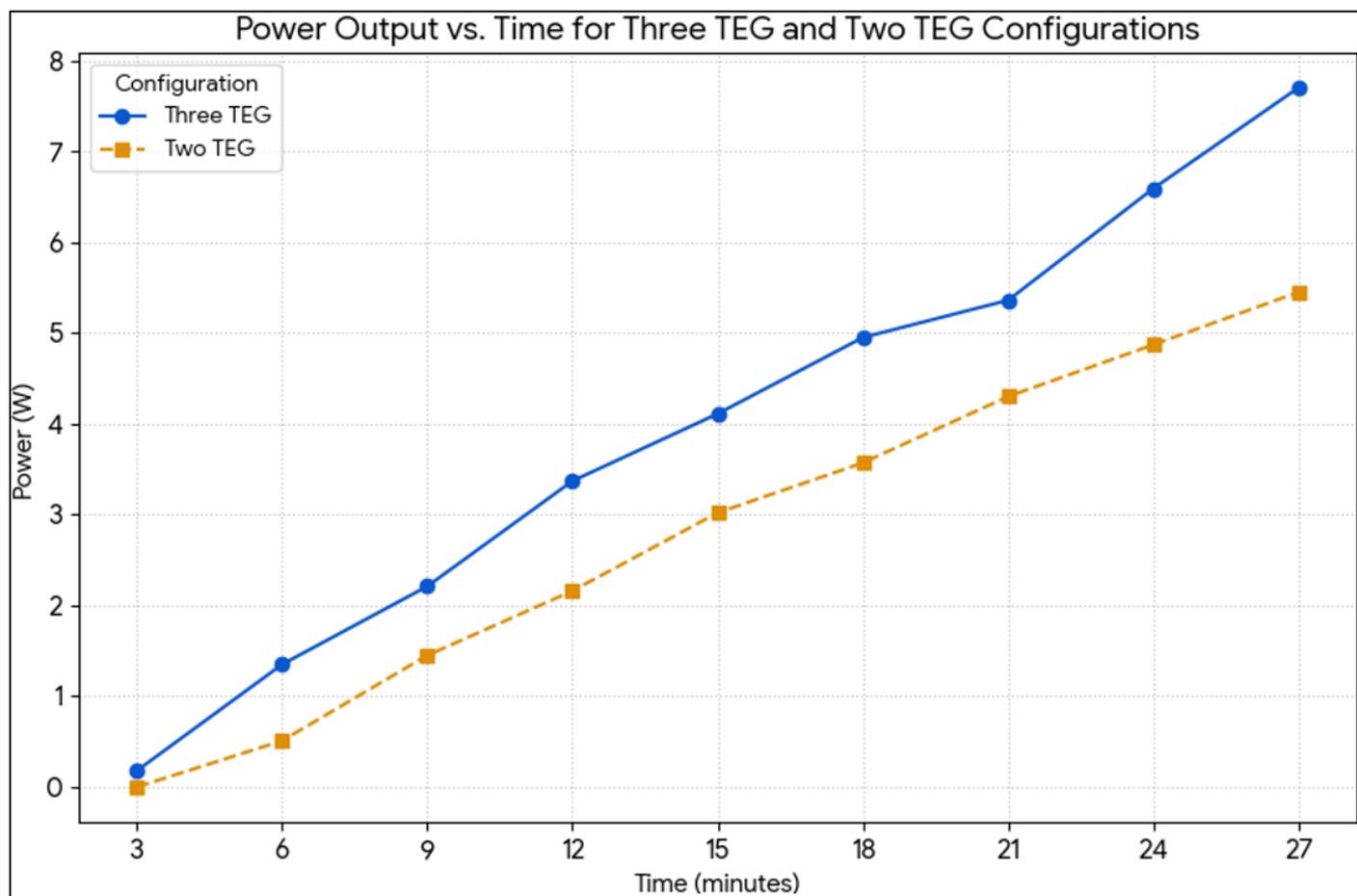
Fig. 7 Power Output vs. Time for both the Three TEG and Two TEG configurations

Figure 7 shows that both approach' power output rises with respect to time, while the three-TEG set up invariably generates higher and rapid-growing power than the two-TEG system. In about 27 minutes, the three-TEG gained 7.8 W in contrast to 5.3 W, suggesting that more modules would definitely enhance the efficiency and at the same time broaden the performance gap over time.

➢ *Two-Way ANOVA Summary for Voltage, Current, and Power*

Table 5 Voltage

Source	Sum of Squares	df	Mean Square	F	p-value
TEG Type	2.000	1	2.000	1.687	0.215
Time	65.077	1	65.077	54.898	0.000003
TEG Type × Time	0.650	1	0.650	0.548	0.471
Residual	16.596	14	1.185	---	---

Table 5 reveals that time had a significant effect on voltage output (F = 54.90, p < 0.001), stipulating that voltage rises steadily as the temperature difference increases. In contrast, TEG type (p = 0.215) and the interconnection between TEG type and time (p = 0.471) were not significant. In general, the voltage increase was motivated primarily by heating time instead of the number of modules, with both set up achieving similar voltage and time sequence.

Table 6 Current

Source	Sum of Squares	df	Mean Square	F	p-value
TEG Type	0.1136	1	0.1136	36.069	0.000032
Time	0.9974	1	0.9974	316.655	5.2×10^{-11}
TEG Type × Time	0.00363	1	0.00363	1.152	0.302
Residual	0.04410	14	0.00315	---	---

Table 6 presents both TEG type (F = 36.07, p < 0.001) and time (F = 316.66, p < 0.001) having significant effects on current output, while their interaction was not significant (p = 0.302). This clearly shows that the variables impacted current independently.

The 3-TEG system continually produced higher current across all time points, but the difference between the two systems stays constant progressively with time.

Table 7 Power

Source	Sum of Squares	df	Mean Square	F	p-value
TEG Type	6.113	1	6.113	179.837	2.22×10^{-9}
Time	76.273	1	76.273	2243.727	7.40×10^{-17}
TEG Type $\times$ Time	1.139	1	1.139	33.500	0.000047
Residual	0.476	14	0.0340	-	-

Table 7 shows that power output was vigorously affected by all variables: TEG type (F = 179.84, p < 0.001) and time (F = 2243.73, p < 0.001) were both immensely significant, and their relation was also significant (F = 33.50, p < 0.001). This signify that both the number of modules and heating time vastly influence power generation. and the significant interaction means the performance gap between the systems increases over time, with the 3-TEG setup producing much more power at higher temperature differences.

IV. CONCLUSION

This study denotes the possibility of harvesting electrical energy from stove generated waste heat using thermoelectric generator (TEG) modules. Briquette fuel was established to be more functional when compared to lump charcoal, making use of less energy input of (490 kJ vs. 730 kJ) while attaining higher thermal efficiency (65.3% vs. 43.8%). The electrical production of the two and three TEG configurations disclosed that additional number of modules and heating duration considerably augmented the power output, as validated by two-way ANOVA analysis. These results not only corroborate earlier findings in thermoelectric energy research but also furnished us with operational insights for optimizing stove based energy harvesting systems. Overall, the study underscores the potential of integrating TEG modules with efficient cooking fuels as a justifiable approach to converting waste heat into useful electrical energy.

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