CEDS Journal of Entrepreneurship and Innovation Research
Vol. 3 No. 2, December, 2024

SOLAR-THERMAL ELECTRICITY GENERATION IN MUBI, NIGERIA

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ABSTRACT

Electricity supply poses a significant challenge in Nigeria, predominantly sourced from fossil fuels, contributing to environmental pollution and facing rapid depletion. In this study, a thermal solar electricity generation system was designed and built to address this issue. Utilizing the See-beck effect, thermoelectric materials convert solar heat radiation into electrical energy. The system comprises four iron-sheet troughs (0.1mm thickness, 0.60m width, 1.22m length), supported by square iron pipes (0.25m x 0.25m) forming a parabolic trough holder (1.22m x 1.83m). To enhance solar concentration, plane mirrors were segmented into smaller rectangular pieces (0.05m x 0.30m and 0.05m x 1.0m) for precise reflection along the parabolic path. Ninety-six thermocouples were strategically positioned on the focal receiver of the troughs, spaced at 0.04m intervals, and connected in series. The system achieved a voltage output of 2.1mV at 56°C (329K). This solar thermal electricity generation system is ideally suited for rural applications, particularly in areas like northern Nigeria with abundant solar radiation and limited access to conventional power grids. If effectively harnessed, this technology presents a promising alternative to non-renewable energy sources such as fossil fuels.

Keywords: Electricity, Solar-energy, thermal energy, Thermocouple, Heat and Solar-collectors

1.0 Introduction

Nigeria, with a vast land mass of approximately 9.24×10^5 km^2 benefits from abundant solar energy resources due to its tropical location. The country experiences an average of 6.25 hours of sunshine daily, ranging from 3.5 hours in the coastal regions to 9.0 hours in the far northern areas (Sambo et al., 2012). Despite this favorable solar energy potential, Nigeria faces persistent challenges in its energy sector, which significantly affect its socio-economic development.

The Nigerian power sector is characterized by insufficient generation capacity, unreliable supply, and high transmission and distribution losses. These deficiencies result in frequent power outages, which have cascading effects on the economy, including increased costs of doing business, reduced productivity, resource waste, and poor service delivery (Ndukwu et al., 2021). Although the installed electricity generation capacity is estimated at over 13,000 MW, actual output often hovers around 4,000 MW due to inadequate infrastructure, maintenance issues, and fuel supply constraints. The reliance on fossil fuels for electricity generation further exacerbates the challenges, as it contributes to environmental degradation and greenhouse gas emissions.

Globally, solar energy has emerged as a vital component of renewable energy initiatives, offering a clean, sustainable, and increasingly cost-effective alternative to fossil fuels. Countries like Germany, the United States, and China have made significant strides in solar energy adoption, demonstrating its feasibility as a reliable energy source. These advancements have been driven by technological innovations, policy incentives, and the global commitment to combat climate change.

However, the adoption of solar energy technologies in the region remains limited despite the availability of high solar insolation levels. The annual average daily solar radiation in Nigeria is approximately 5.25 kWh/m2/day with values reaching 9.0 kWh/m2/day in the northern regions (Aggrey & Ibrahim, 2018). These figures suggest a significant untapped potential for solar energy utilization, which could alleviate the country's energy crisis and reduce its carbon footprint.

While there is substantial literature on the potential of solar energy in Nigeria, many studies lack empirical data specific to regional applications and fail to address the integration of solar technologies into the national energy mix. For instance, studies often focus on theoretical assessments of solar potential without considering the socio-economic and technical barriers to adoption. Furthermore, there is limited research on innovative solar technologies, such as solar thermal systems, and their applicability in the Nigerian context. Addressing these gaps requires a comprehensive approach that combines theoretical reviews with empirical analyses.

Theoretically, solar energy systems, including photovoltaic (PV) and solar thermal technologies, are grounded in the principles of thermodynamics and semiconductor physics. Solar thermal systems, in particular, capture and concentrate sunlight to produce heat, which is then used to generate electricity. Empirical studies have demonstrated the effectiveness of solar thermal technologies in regions with high solar insolation. For example, Naydenoy (2019) highlights the cost-efficiency of parabolic trough systems, which have become a benchmark for large-scale solar power generation globally.

In this context, empirical studies are needed to evaluate the performance of solar thermal systems under local environmental conditions. Additionally, research should explore the economic feasibility and scalability of these systems in rural and urban settings. The study not only underscores the potential of solar energy in Nigeria but also bridges the gap between theoretical assessments and practical applications, paving the way for sustainable energy solutions.

1.2 Objectives

To address the identified gaps, this study aims to:

a) Investigate the relationship between solar radiation (temperature) and solar energy density within Mubi.
b) Examine the voltage (V) generated by the Seebeck effect using thermocouples.
c) Develop a cost-effective solar thermal system capable of generating electricity.

2.0 Review of solar energy generation and its technologies

Solar energy gained significant attention following the 1973 oil crisis, which emphasized the need for environmentally friendly renewable energy sources (Pabio, Critina & Pere, 2018). Since then, research and development have greatly advanced solar technologies. Solar-thermal systems, in particular, offer many advantages as they harness an abundant and renewable energy source. These systems, when combined with energy storage technologies such as batteries, can supply electricity even during nighttime hours. Recent advancements have improved the efficiency of solar-thermal systems, achieving conversion efficiencies of 10-25%, with potential to reach up to 30% (Costa, Del & Trujillo, 2018). While these efficiencies are modest, improvements in manufacturing techniques could help enhance performance. Solar-thermal electricity generation, or solar-thermal power plants, concentrate solar radiation at high temperatures (300°C to 800°C) to produce electricity (Mishra & Tripathy, 2012).

a) Solar Thermal Collection Technologies: Several collection technologies have been developed to harness solar energy:
b) Parabolic Trough Systems: These systems use curved mirrors to focus sunlight onto a receiver tube, transferring heat to a fluid, which generates steam to drive a turbine (Powell et al., 2017).
c) Heliostat or Central Receiver Power Plants: Mirrors reflect sunlight onto a central tower, where heat is absorbed by molten nitrate salt, generating steam to power a turbine (Aguannol et al., 2018; Benyakhlef et al., 2016).
d) Solar Chimney Power Plants: Hot air rises through a tall chimney, driving a wind turbine to generate electricity (Md Tasbirul et al., 2018).
e) Dish Stirling Systems: These systems focus sunlight using parabolic mirrors to heat gas in a chamber, producing mechanical energy to generate electricity (Ugo et al., 2017).
f) Solar Ponds: Saltwater pools trap heat using a salinity gradient, which can be used for power generation (Mohammad et al., 2018).

2.1 Thermoelectric energy conversion

Thermocouples, which convert thermal energy into electrical energy, have been instrumental in thermoelectric energy conversion since the 18th century. They operate based on three key phenomena: the Seebeck, Peltier, and Thomson effects. The Seebeck effect generates an electric current when two dissimilar metals are subjected to a temperature gradient, providing the foundation for thermoelectric energy generation. This principle is widely used in harnessing waste heat from industrial processes or natural sources to produce electricity (Kok et al., 2018).

The Peltier effect involves the transfer of heat through a junction by an electric current, leading to either absorption or release of heat. This effect is crucial for thermoelectric cooling and power generation. It enables precise temperature regulation in various applications, including scientific and medical devices, while also contributing to the efficiency of thermoelectric generators (Pokrovskii, 2020). Additionally, the Thomson effect, though less prominent, describes the heating or cooling in a conductor caused by an electric current flowing through a temperature gradient, further enhancing system performance (Igor et al., 2018).

Together, these effects underpin thermoelectric generators (TEGs), which offer promising potential as sustainable energy solutions. With advancements in thermoelectric materials and system design, TEGs are approaching efficiency levels comparable to photovoltaic systems. This progress highlights their viability for renewable energy production, particularly in converting waste heat into usable energy, making them a competitive alternative in the field of sustainable energy (Bellucci et al., 2021; Gurpreet & Jaspreet, 2023).

3.0 Material and Method

3.1 Materials

The materials used for the construction of solar thermal system electricity generator are:

1.	Iron stand	2.	Thermocouples
3.	Troughs holder	4.	Multimeter
5.	Parabolic troughs	6.	Bolts and nuts/washers
7.	Three-quarter inches iron pipes	8.	Masking tape
9.	Plane mirrors	10.	Body filler
11.	Constantan wires	12.	Paint
13.	Copper wires		

Table 1:

Trough size and geometry, materials and transducer used plays key role in the design decisions and the electrical output budgeted for. The entire design process was done step by step and system by system. Thus, the block diagram in Figure 1 below illustrates the approaches taken to achieve the design.

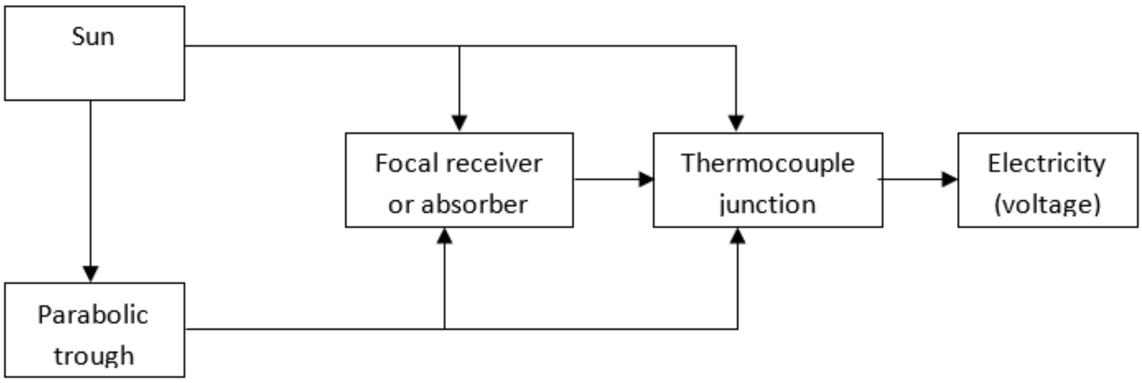

Figure 1: Block diagram of solar thermal electricity generation

Step (1): This plant makes use of a large field of parabolic trough collectors that track the sun during the day. First, the troughs were measured, cut, bent, polished, and built according to the dimensions shown in Table 1. The specifications were created based on the magnitude of the voltage that would be produced. The diameter of a flat circular sheet of material (metal) troughs was calculated, measured, bent along its surface, and cut to the appropriate size. This was obtained by applying the relationship:

$$p = 2F \quad (1)$$

Or the equivalent

$$p = \frac{R^2}{2D} \quad (2)$$

Where R is the radius of the rim, D the depth of the trough measured along the axis of symmetry from the vertex to the plane of the rim and F is the focal length. In this research, 60cm size was considered right for the project.

The dimension of the symmetrical paraboloidal trough are related by the equation.

$$4FD = R^2 \quad (3)$$

This equation can be used to calculate the third of these three quantities if two of them are known. Because the trough curve was chosen at 60cm, the diameter is 50cm and the radius is 25cm. As a result, the focal length can be calculated using the equation (3.3)

$$F = \frac{(25)^2}{40} = 15.63cm \quad (4)$$

The troughs were made of 0.1mm thick iron sheet with dimensions of 0.60m x 1.22m. Each of the four troughs is 0.1mm thick and 0.60m x 1.22m in size. The upper trough holder is 1.5mm thick and 0.10m x 1.22m in size, while the lower trough holder is 2.00mm thick and 0.15m x 1.00m in size. Each thermocouple is made of copper wire with a thickness of 0.75mm and a length of 0.60m, as well as constantan wire with a thickness of 0.25mm and a length of 0.60m.

Step 2: The absorber is typically an optical device such as mirrors, lenses, plane glass, and so on. To trace the rays in this project, a mirror was used for convenience. Its primary function is to concentrate solar radiation for the thermocouple. Solar radiation is attenuated as it travels through space to the earth's surface. A focal receiver is usually integrated into the system to compensate for this attenuation and make the solar rays stronger.

Step 3: Thermocouple junctions are transducers that convert thermal energy into electrical energy. A thermocouple is typically composed of two wires of dissimilar metals connected at one end and capable of transferring thermal energy as a voltage measured across the cold junction ends. In this experiment, 96 thermocouples made of 0.75mm copper wire and 0.25mm constantan wire were used. The thermocouple junction on the absorber captures and generates electricity from concentrated solar radiation.

Step 4: The dimensions of other accessories used are summarized in the Table 3 below.

Table 2: Dimensions of material and quantity

Names of materials	Dimension (m)	Thickness (mm)	Quantity
Lower trough holder	0.15x 1.00	2.00	1
Upper trough holder	0.10 x 1.22	1.50	4
Trough	0.60 x 1.22	1.10	4
Copper wire	0.6	0.75	96
Constantan wire	0.6	0.25	96
Plane mirror	0.05 x 0.30	3.00	48
Plane mirror	0.05 x 1.00	3.00	48
Square iron pipe	0.25 x 0.25	2.50	5
Trough holder	1.22 x 1.83	2.50	1

Step 5: The parabolic trough stand – the stand is made of two different iron pipes, the base pipe and the top pipe. The base pipe is a galvanized iron pipe with a thickness of 2.0mm, a diameter of 0.15m, and a height of 1m. The top pipe was also made of iron pipe with a

thickness of 1.5mm, a diameter of 0.10m, and a height of 1.22m. As shown in Figure 2, the two different pipes were connected with bolts and nuts and then casted.

3.3 Construction and coupling

The troughs were mounted on a fixed stand and adjusted to Mubi's latitude of 10o 16' using an adjustable nub at an angle of inclination attached to the trough holders. The maximum temperature that the trough can generate was measured using a thermometer, though it varies depending on the weather.

Figure 2: Parabolic trough stand casted ready for mounting

After mounting the troughs, the thermocouples were arranged on the focal receiver of each trough, which has a capacity of 29 thermocouples separated by 0.04m. The total number of thermocouples on the four troughs is 96.

Figure 3**:** Arrangement of thermocouple

As illustrated in Figure 3, all 96 thermocouples were wired in series so that the total voltage generated by the solar thermal generator equals the sum of the voltages generated by each thermocouple, i.e.

$$V_T = (V_1 + V_2 + V_3 + ---- + V_{96}) \quad (5)$$

Alternatively, the voltage in a thermoelectric circuit can be represented as a product of the see-beck coefficient and temperature differences at each junction. As a result, the total voltage produced by the solar thermal generator can be written as:

$$V_T = (S_A - S_B)(T_M - T_J) + (S_{A2} - S_{B2})(T_{M2} - T_{J2}) + (S_{A3} - S_{B3})(T_{M3} - T_{J3}) + ---- + (S_{A96} - S_{B96})(T_{M96} - T_{J96}) \quad (6)$$

The current passing through the circuit is constant, since the connections are in series.

Figure 4: A complete system of the solar-thermal generation of electricity

4.0 Results and Discussion

4.1 Results

The digital clock and a digital multi-meter were used to collect the data in Table 4.1. Time was measured using a digital clock, and potential difference (Pd) and temperature were measured using a digital multimeter.

Table 3: Data obtained in the first reading (day one 14th May, 2024)

Time (hr)	Temperature (oC)	Temperature (K)	Voltage (10mV)
7:30	28.5	301.5	3.70
8:00	31.0	304.0	5.50
8:30	33.0	306.0	7.50
9:00	34.5	307.5	8.70
9:30	37.0	310.0	9.10
11:00	40.0	313.0	9.50
12:30	42.0	315.0	9.70
1:00	43.0	316.0	11.00
1:30	42.0	315.0	9.70
2:00	44.0	317.0	13.00
2:30	43.0	316.0	11.00

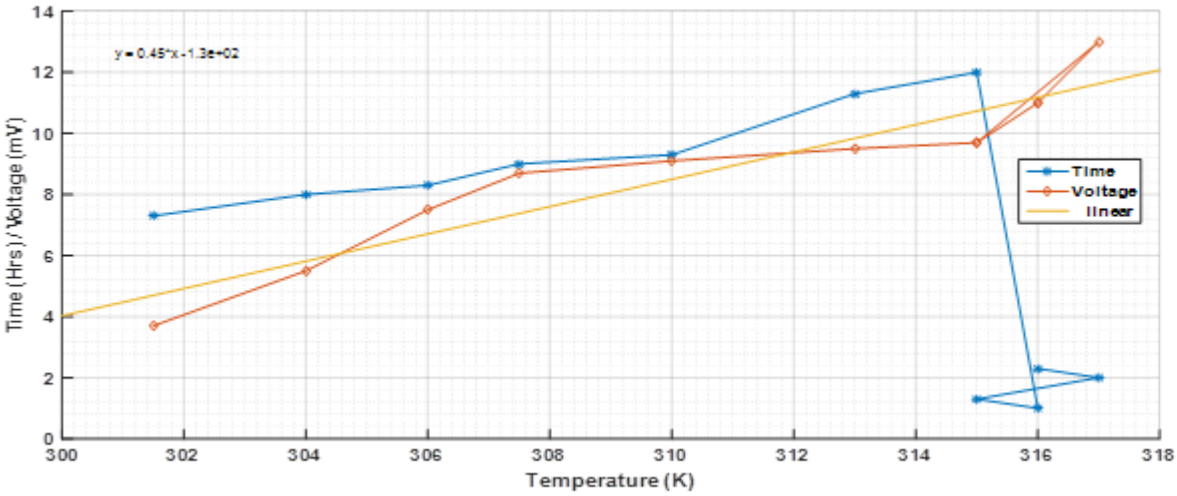

Figure 5: The graph of voltage (mv) and Time (hrs) against Temperature (k) for day one

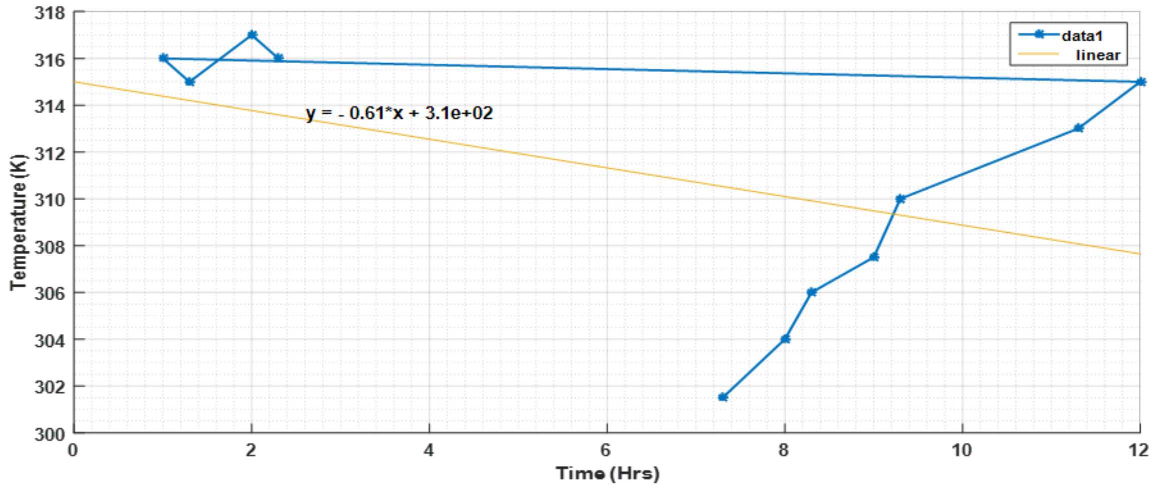

Figure 6: The graph of Temperature (k) against Time (hrs) thermal conductivity for day one

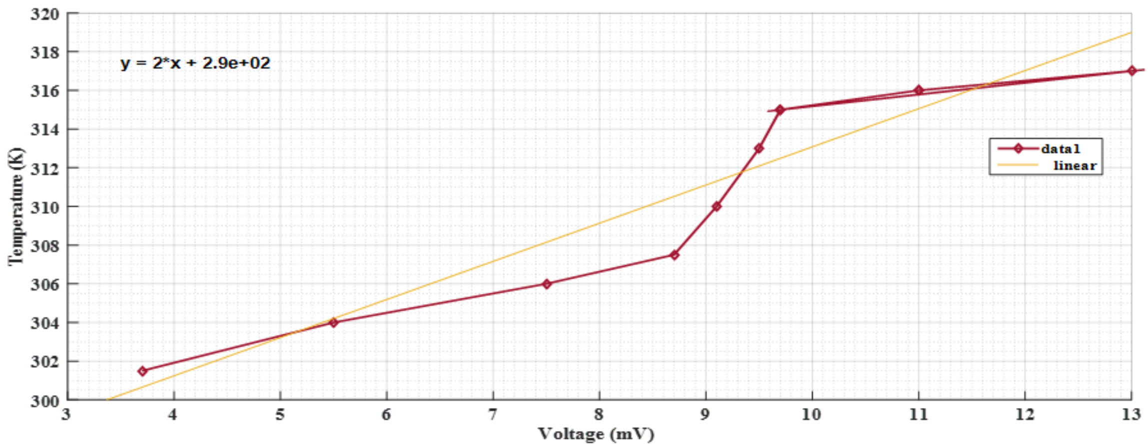

Figure 7: The graph of Temperature (k) against Voltage (mV) thermal conductivity for day one

Table 4: Data obtained in the second readings (day two 15th May, 2024)

Time (hr)	Temperature (oC)	Temperature (K)	Voltage (mV)
7:30	28.0	301.0	0.35
8:00	31.0	304.0	0.55
8:30	32.5	305.0	0.70
9:00	34.5	307.5	0.87
9:30	37.0	310.0	0.91
10:00	40.0	313.0	0.95
10:30	42.0	315.0	0.97
11:00	43.0	316.0	1.10
11:30	40.0	313.0	0.95
1:30	42.0	315.0	0.97
2:00	42.0	315.0	0.97
2:30	43.0	316.0	1.10

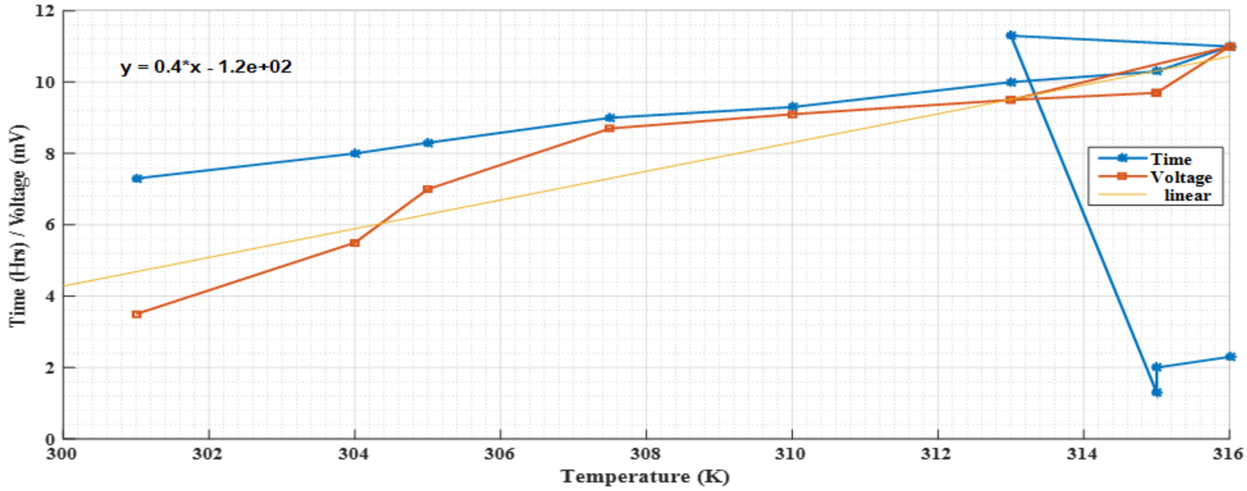

Figure 8: The graph of voltage (mv) and Time (hrs) against Temperature (k) thermal coefficient /heat flow for day two

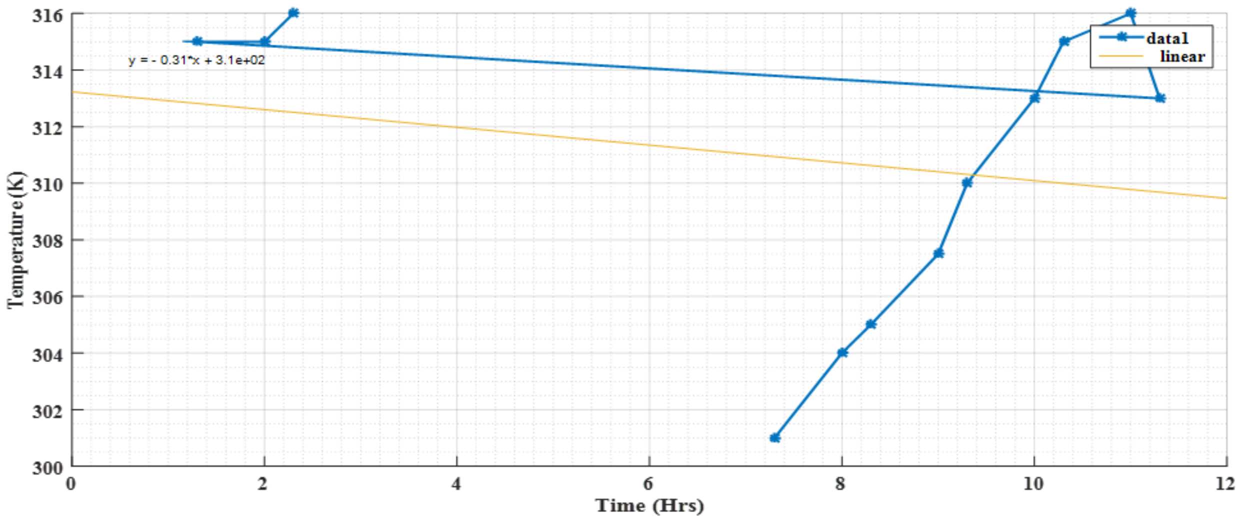

Figure 9: The graph of Temperature (k) against Time (hrs) thermal conductivity for day two

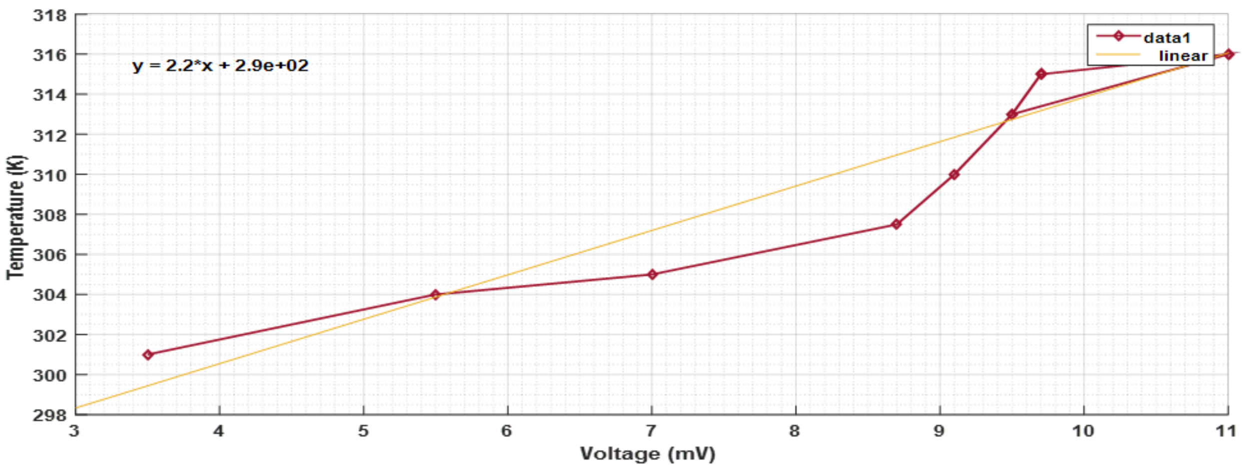

Figure 10: The graph of Temperature (k) against Voltage (mV) thermal conductivity for day two

Table 5: Data obtained in the third reading (day three 16th May, 2024)

Time (hr)	Temperature (oC)	Temperature (K)	Voltage (mV)
7:30	28	301	0.35
8	30	303	0.5
8:30	32.5	305.5	0.7
9:00	34	307	0.85
9:30	35	308	0.9
10:00	40	313	0.95
10:30	42	315	0.97
11:00	43	316	1.1
11:30	44	317	1.3
12:00	47	320	1.4
12:30	50	323	1.5
1:00	55	328	1.8
1:30	54	327	1.7
2:00	56	329	2.1
2:30	53	326	1.65

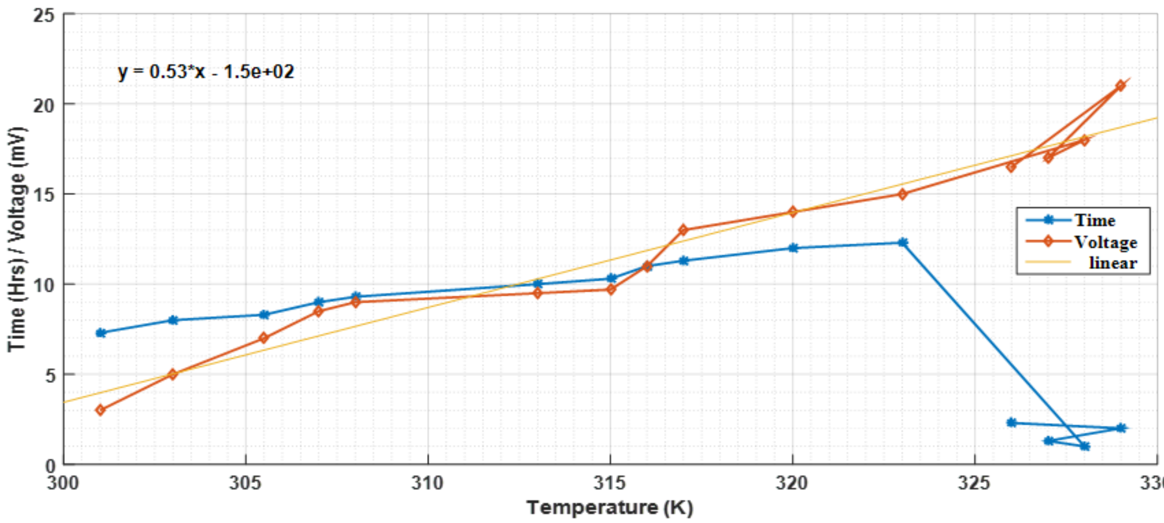

Figure 11: The graph of voltage (mv) and Time (hrs) against Temperature (k) thermal coefficient / heat flow for day three

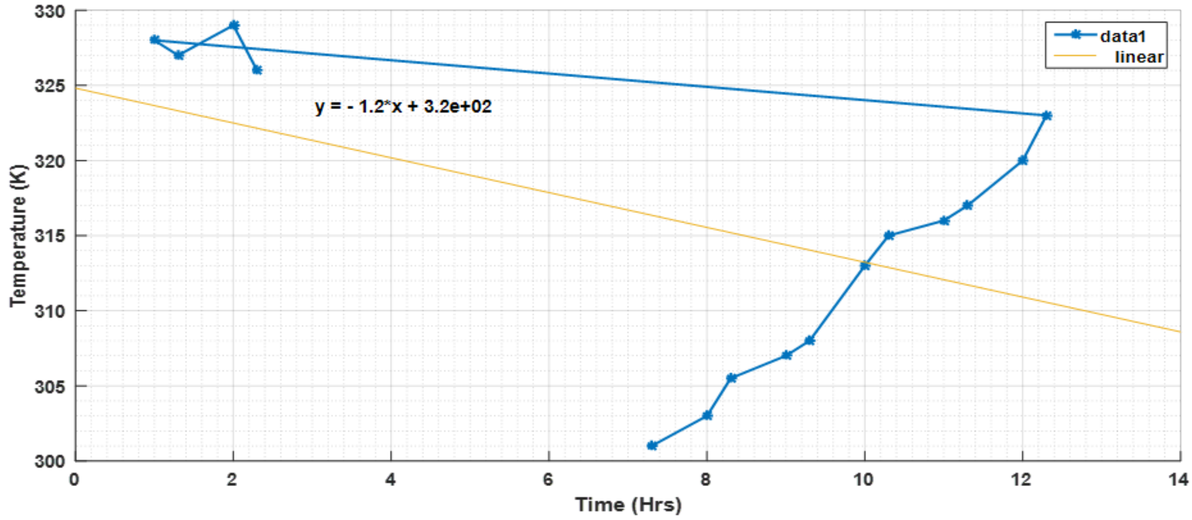

Figure 12: The graph of Temperature (k) against Time (hrs) thermal conductivity for day three

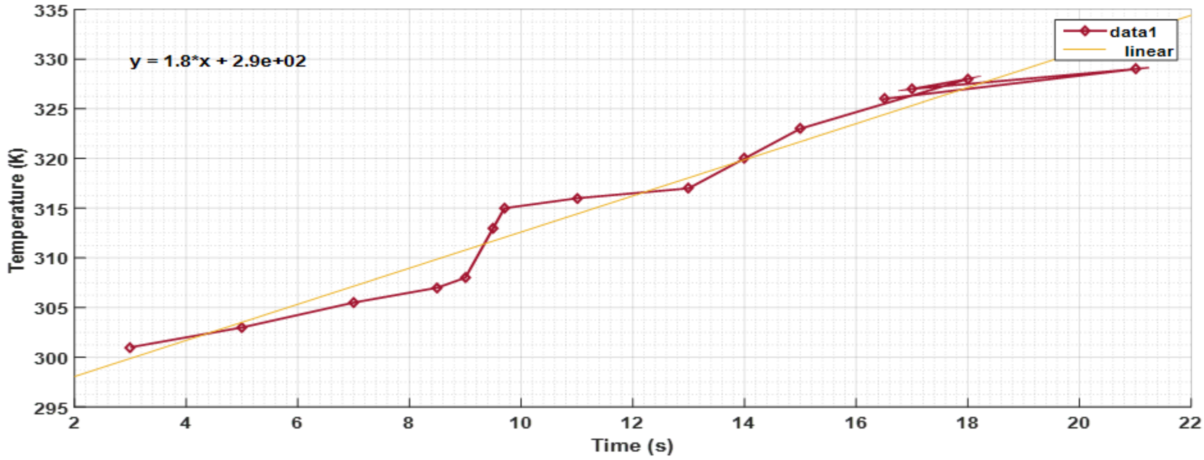

Figure 13: The graph of Temperature (k) against Voltage (mV) thermal conductivity for day three

4.2 Discussion

Solar thermal energy generation is the direct application of solar energy to produce heat, which is then used as a source of energy to power a load such as nuclear fuel, fossil fuel, and other non-renewable energy sources. Because others are not environmentally friendly, emitting greenhouse gases into the atmosphere and contributing to global warming, renewable energy such as this is preferred.

Figures 5, 8, and 11 show graphs of millivolt voltages and time in hours versus temperature in Kelvin, which is the thermoelectric coefficient/heat flow. These relationships show that as the temperature difference in the system increases, so does the voltage created by the see-beck coefficient. The figures above clearly show that all of the highest voltages were generated at high temperatures, which decays at peak temperature, which is usually 2:00 pm to 2:30 pm on a sunny day. This was due to a reduction in the amount of solar radiation reaching the troughs, as well as the surrounding buildings and trees.

Figures 6, 9, and 12 show graphs of thermal conductivity versus temperature in Kelvin over time in hours. These results show that the thermal conductivity of the system increases as the temperature rises. Though the temperature increased throughout the day due to the season, the cloud cover directly affects the solar radiation reaching the troughs, causing a decrease in temperature. As shown in the graphs above, this effect was significant on days 1 and 2. Because the third day was sunny, the readings obtained on that day were slightly better.

The system can generate electricity even at room temperature if there is a temperature differences between these two thermocouple junctions of each pair. The system was able to produce 0.35mV at 28 °C (301 K) that is almost ambient temperature and 2.1mV at 56°C (329 K).

Figures 7, 10, and 13 show graphs of temperature (k) versus voltage (mV) thermal conductivity. These demonstrate that the voltage generated is proportional to the temperature.

5.0 Summary and Conclusion

5.1 Summary

A thermal solar system for generating electricity was designed and built. The system generates electricity by harnessing the sun's heat. The system consists of four parabolic troughs made of 0.1 mm metal sheet and a parabolic surface traced with mirrors. Ninety-six thermocouples made of 0.75 mm thick copper wire and 0.25 mm thick constantan wire were used. The thermocouples were arranged on the focal receiver of each trough, which has twenty-nine thermocouples separated by 0.04m. To increase the magnitude of the voltage, the thermocouples were connected in series.

The four troughs were placed on a trough holder made of 0.25 m2 square iron pipe, and the trough holder measures 1.22 m by 1.83 m. The trough holder was fixed to a stand. The mounted trough holder was aligned north-south and tilted 10o 151 so that sunlight cuts across the trough as it passes on its axis from east to west.

The system employs a large field of parabolic trough collectors that track the sun during the day and focus solar radiation on an absorber located at the focal point of the parabolic-shaped mirrors. The thermocouple junctions on the absorber absorb the concentrated solar radiation as well, and a potential difference is established, resulting in the generation of electricity. The system was able to generate 0.35mV at a temperature of 28oC (301 K), which is almost ambient, and 2.1 mV at a temperature of 56oC (329 K).

5.2 Conclusion

Thermal solar energy generation is a tested technology that is particularly well-suited for use in rural areas where a large population remains disconnected from the existing power grid. Because of the lower cost of maintenance and the free energy source that powers the system, the electric energy generated by thermal solar systems provides superior, more reliable, and more convenient services for a life circle cost that is comparable to or less than what households are already paying. The system's ability to provide sufficient stability and relatively low implementation costs makes it very feasible for use in solar-to-electricity conversion on both a small and large scale. The system's simplicity of design makes it very reliable for long-term operation. Hence when installed, the system can go on automatically.

For many rural areas in Africa, the sun is often viewed as a formidable ally for raising crops or, conversely, for weathering crops and dashing hope. Solar radiation, when harnessed, can be a powerful ally via solar cookers, steam engines, parabolic troughs, and thermocouples. The sun is becoming an important source of energy, offering an alternative to conventional electric power plants, diesel fuel, and wood fuel, among other things.

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