Design, Fabrication, and Performance Evaluation of a Small-Scale Hybrid Solar Thermal Parabolic Trough System with Auxiliary Gas Heating for Electricity Generation in Nigeria

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ABSTRACT

Energy plays a fundamental role in economic development and technological advancement. Nigeria continues to experience persistent electricity shortages due to limited generation capacity and increasing energy demand. Given the country's high solar radiation potential, solar thermal technologies offer a promising option for decentralized electricity generation. This study presents the design, fabrication, and experimental evaluation of a small-scale hybrid solar thermal parabolic trough collector (PTC) system for electricity generation. The system consists of a 4 m long parabolic trough collector with acrylic mirror reflectors, a borosilicate glass receiver tube, water as the heat transfer fluid, a single-axis solar tracking mechanism, an auxiliary liquefied petroleum gas (LPG) heating unit, and a compact impulse steam turbine coupled to a DC generator. Experimental tests were conducted over three consecutive days between 09:00 AM and 05:00 PM. The system produced a peak electrical power output of 40.79 W. Short-duration instantaneous efficiency values approaching 26% were observed during periods of high solar irradiance; however, the average overall solar-to-electric efficiency during the experimental period was approximately 7.9%. The hybrid configuration improved operational stability during periods of low solar radiation. Performance limitations were mainly associated with low steam mass flow rate, thermal losses in the receiver and piping, and the limited efficiency of the small impulse turbine. The results demonstrate the feasibility of locally fabricated hybrid solar thermal systems for small-scale off-grid electricity generation in developing regions.

Keywords:
Concentrated Solar Power,
Hybrid System,
Superheated Steam,
Electricity Generation,
Nigeria.

INTRODUCTION

The driving force of modern civilization is energy, which has an effect on every aspect of human life and is closely related to social benefits, ecological protection, industrial development, and technological progress. The World population is on the rise and so is the level of energy consumption" With rapid urbanization and industrialization the energy necessity is growing at an alarming rate.

More than a decade ago, the International Energy Agency (2023) reported that world energy demand has been rising continuously during the last quarter of a century and that a considerable amount of this growth has materialized in developing countries.

In Sub-Sahara Africa and Nigeria, specifically, the growing demand is not being sufficiently met because of various systemic limitations. Now, despite its wealth in people and nature, Nigeria grapples with an unremitting power problem. The capacity of the national grid is limited due to generation shortages, old transmission lines, and high transmission and non-transmission losses. The country's installed generation capacity is estimated at 12,500 MW of which only about 4,000 MW is usually available for utilization because of several operational ineffectiveness (Adoghe et al., 2023; Oyedokun et al., 2022). This deficiency has resulted in a very high dependence on diesel generators, for both domestic and industrial utilizations, which has led to soaring carbon emissions, as well as elevated operational costs (Oladokun & Asemota, 2015).

To address these challenges, Nigeria's Renewable Energy Master Plan (REMP) identifies a target to raise the share of power generated from renewable sources to be at least 20% by 2030 (Akuru & Okoro, 2014). One such is solar

energy which appears to be very promising given the geographical location of Nigeria within latitudes 4°N to 14°N and having average solar radiation of 4.5 to 7.0 kWh/m²/day, and over 2600 hours of annual sunshine (Njoku, 2014).

In terms of both centralized and decentralized solar applications, this is quite encouraging for Nigeria.

There are two means for collecting solar energy: photovoltaic (PV) and solar thermal systems. While solar thermal systems concentrate sunlight and transform it into heat that can be utilized to physically generate power, photovoltaic technologies directly convert sunlight into electricity (Kalogirou, 2004). While PV systems are popular due to their adaptability, solar thermal technologies have different advantages in terms of energy storage, thermal capacity, and hybrid integration with fossil fuels.

The parabolic trough collector (PTC) is a mature and efficient solar thermal energy technology. A PTC system focuses solar light onto a linear receiver at the focal line of the trough using curved, reflecting surfaces. This receiver receives concentrated thermal energy and sends it to a turbine or generator to produce electricity. It contains a heat transfer fluid (HTF), such as water, molten salt, or synthetic oil (Duffie & Beckman, 2013). PTC systems have been shown to offer excellent conversion efficiency, scalability, and dependability, especially in hybrid arrangements where additional heat from fossil fuels guarantees continuous operation at night or in cloudy conditions (Coventry, 2005; Singh et al., 2000).

PTC systems are becoming more and more seen in Nigeria as workable answers to the problems of energy access and rural electrification. Numerous studies have shown how appropriate they are for developing nations, particularly when made with locally accessible materials. For instance, Torres et al. (2020) and Orosz et al. (2016) showed how cost-effective components such as acrylic mirrors (Shanmugan et al., 2008) and borosilicate glass (Lei et al., 2012) can be utilized in developing PTC systems adapted to the economic constraints of rural populations. In addition to lowering total system costs, local material sourcing improves maintainability and encourages community skill development (Opara & Elekalachi, 2017).

Small-scale parabolic trough systems designed for decentralized electricity generation remain relatively under-reported compared with large commercial concentrated solar power plants. While commercial parabolic trough power plants typically achieve solar-to-electric efficiencies between 15% and 25%, prototype-scale systems often exhibit significantly lower efficiencies due to optical losses, heat losses from receivers and piping, low steam mass flow rates, and the limited efficiency of small turbines and generators. Reported efficiencies for experimental small-scale PTC-steam systems commonly fall within the range of 5–12%

depending on system design, heat transfer characteristics, and operating conditions. Nevertheless, small-scale hybrid systems remain attractive for rural electrification because they can be constructed using locally available materials and can maintain operation under intermittent solar conditions.

In this study, a combination of parabolic trough collector, solar receiver, auxiliary gas burner heat source (superheater), and steam turbine electric generator were developed based on previous studies. The system can generate power under circumstances of little solar radiation. It mitigates the weather-dependent and diurnal cycles induced intermittency of the solar-only systems, as one of the main limitations of solar-only systems is mitigated by hybridization of the solar input with an auxiliary thermal source (Powell et al., 2017; Ahmadi et al., 2018). The design requires a 4-meter (m) long parabolic trough with a 2.03 meters (m) aperture width and 0.61 meters (m) depth. This provides an optimal geometric concentration ratio for efficient heat acceptance. The receiver was made with a borosilicate glass tube and blackened to provide high absorptivity and heat retention. Water was employed as a heat transfer fluid (HTF) to absorb, transport, and transfer thermal energy from the solar receiver. The saturated heat steam or partially heated water exits the solar receiver and is sent via an insulated rubber piping tube to the auxiliary gas burner portion. This produces superheated steam (high energy steam) that can spin a compact impulsive steam turbine, coupled to a 0.065KW DC generator to generate electricity. The PTC system was placed on a single-axis solar tracker to take advantage of good insolation (Takilalte et al., 2023).

This study stands out for its emphasis on indigenous creativity, where the majority of the materials employed were sourced locally. This approach is not only suitable for economic limitation but also advance for domestic fabrication development as reported by Olaoye et al. (2022) and Olaopa and Ayodele (2022), emphasizing the importance of community-based energy responses in Africa. Despite the extensive development of large-scale concentrated solar power plants worldwide, experimental studies on small-scale hybrid parabolic trough systems suitable for decentralized electricity generation in Africa remain limited. In particular, few studies have investigated locally fabricated hybrid solar thermal systems that integrate auxiliary heating to improve operational reliability under variable solar conditions. The objectives of this study are to: (i) design and construct a locally optimized parabolic trough collector; (ii) integrate a solar and auxiliary heat source for hybrid electricity generation; and (iii) analyze the performance of the system based on operation parameters including temperature difference, solar irradiance, electric power output, and thermal-to-electric efficiency. These measures were collected over three days and analyzed

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using energy balance equations and first-law thermodynamic efficiency formulas (Kalogirou, 2009; Duffie & Beckman, 2013; Jebasingh & Herbert, 2016). Beyond its technical scope, this work has significant environmental and socioeconomic implications. By reducing reliance on diesel and coal-based generators, hybrid solar thermal systems contribute to lower greenhouse gas emissions and promote environmental sustainability. Moreover, decentralized renewable energy systems create opportunities for employment, skill acquisition, and local enterprise development, particularly in underserved regions. These benefits are in line with the United Nations Sustainable Development Goals, especially SDG 7 ("Affordable and Clean Energy") and SDG 13 ("Climate Action") (United Nations Department of Economic & Social Affairs, 2020; International Energy Agency, 2022).

MATERIALS AND METHODS

The hybrid solar thermal power generation system in this study consists of a water storage tank, a parabolic trough collector (PTC), a solar receiver, a heat transfer fluid (HTF), an auxiliary gas burner (superheater), a compact impulse steam turbine coupled with an electric generator, an automatic single-axis sun-tracking mechanism, and a power generation room housing the steam turbine electric generator and other devices.

Water Storage Tank

The water storage tank was constructed from a 2 mm thick iron sheet and has a total capacity of 180 liters. Its height was 0.61 meters (m) and its base radius was 0.31 meters (m). The tank is mounted on a metal supporting structure above the parabolic trough to allow gravity-fed release and effective water storage. The metal structure, which stands 2.74 meters (m) tall and 0.62 meters (m) wide, was composed of angled iron of thickness 4 mm and was developed to ensure dependable functioning and excellent mechanical stability in adverse weather situations such as strong winds.

Parabolic Trough Collector (PTC)

The PTC in this research, which is the system's primary solar concentration, was constructed from acrylic mirror reflective sheets. These reflective metal sheets have high reflectivity (above 90%), are cost-effective, and are lightweight, making them ideal for local solar applications (Shanmugan et., 2008). The solar energy capture of the designed PTC, with a length of 4.00 m, depth of 2.03 m, and width of 2.03 m, was computed using the following equation:

$$A_{ap,c} = a \cdot L \qquad (1)$$

Where:
$A_{ap \cdot c}$ – Aperture area of the collector [m²]
a – Aperture width [m]
L – Length of the collector [m]

A larger aperture area increases the potential for solar energy input (Duffie & Beckman, 2013).

Solar Receiver

The solar receiver, known also in this study as the absorber tube, is made up of a 4.00 m long borosilicate glass tube that surrounds a black-painted copper tube in a vacuum. The receiver takes focused sunlight, turns it into heat, and then transfers that heat to a working fluid, which then performs the energy conversion, and the area effectively exposed to the radiation, denoted as $A_{ap.r}$, is calculated as:

$$A_{ap,r} = 2\pi r_r \cdot L \qquad (2)$$

Where:
$A_{ap,r}$ – Aperture area of the receiver (m²)
r_r – Radius of the receiver (m)
L – Length of the receiver (m)
This area has a direct influence on the thermal energy transfer rate to the HTF (Padilla et al., 2011).

Concentration Ratio and Rim Angle

The performance of a parabolic trough collector (PTC) largely depends on its concentration ratio and rim angle. The concentration ratio is defined as the ratio of the collector aperture area to the receiver area (Duffie & Beckman, 2013) and is expressed as:

$$C_G = \frac{A_{ap,c}}{A_{ap,r}} \qquad (3)$$

Where:
C_G – Concentration ratio (–)
$A_{ap,c}$ – Aperture area of the collector (m²)
$A_{ap,r}$ – Aperture area of the receiver (m²)
Similarly, the rim angle is the angle between the axis of the parabola and the line from the focus to the rim of the aperture, influencing the collector's acceptance angle and optical performance. The designed parabolic trough collector (PTC) in this study has a concentration ratio of 24 and a rim angle of 80°. These obtained values fall within the optimal range for high-performance parabolic troughs, where concentration ratios typically vary between 15 and 30 and rim angles range from 70° to 90°. A higher concentration ratio improves the thermal efficiency by increasing the solar flux on the receiver, while a rim angle of 80° provides an effective compromise between high solar concentration and acceptable optical losses (Kalogirou, 2009; Goswami & Kreith, 2017). Therefore, the selected parameters confirm that the developed collector exhibits strong potential for efficient solar thermal energy conversion.

Heat Transfer Fluid (HTF)

Water was selected in this study as the heat transfer fluid due to its high specific heat capacity, availability, and safety. It runs between the receiver and the steam generator. The useful energy absorbed by the HTF is calculated using the equation:

$$Q_{solar} = m \cdot C_p \cdot (T2 - T1) \qquad (4)$$

Where:

Q_{solar} – Thermal energy from solar input (Wh)

m – Mass of fluid (water) (kg)

C_p – Specific heat capacity of water (4180 J/kg·K)

T2 – Receiver outlet temperature (°C)

T1 – Receiver inlet temperature (°C)

This energy balance formulation is standard for evaluating thermal efficiency in solar collector systems (Kalogirou, 2009).

Auxiliary Gas Burner and Compact Impulse Steam Turbine Electric Generator

Steam exiting the receiver as shown in Figure 1 enters a customized pressure vessel of 12-liter capacity made of stainless steel that acts as a steam drum. A 10 kg LPG gas burner was included as a backup thermal source to maintain steam generation during periods of low insolation with the control knob kept constant during the experiment. This dual-input thermal source classifies the system as hybrid (Sarmouk et al., 2021: Akar et al., 2024). The pressurized steam was directed to a compact impulse steam turbine, where it expanded and performed mechanical work. The turbine shaft was mechanically coupled to a 0.065 kW DC generator. The generated electrical power was measured using a digital multimeter, and current and voltage sensors connected to a data logger.

Single-Axis Solar Tracking Device

For this study, a single-axis automatic solar tracker was used to orient the solar collector to follow the sun from an east-west direction to maximize the solar absorption, and the sun's angular position relative (θ) to solar noon and used in solar tracking is expressed as:

$$\theta(t) = \omega(t - t_{noon}) \qquad (5)$$

Where:

ω – Angular velocity of the sun (≈15° per hour)

t – Time (hr)

t_{noon} – Solar noon (12:00 PM)

This approach ensures accurate sun tracking and optimal collector alignment throughout the day (Takilalte et al., 2023).

Power Generation Room

A ventilated stainless steel control room measuring 2.31 m² in area was constructed to house the turbine assembly, pressure vessel, piping, and electrical instruments, and the safety components such as pressure relief valves, pressure and temperature sensors, and heat insulation were integrated to mitigate risks and improve system reliability.

Testing Protocol and Performance Evaluation

The hybrid solar thermal parabolic trough system was tested over three consecutive days, from December 9 to 11, 2019, between 9:00 AM and 5:00 PM daily. During the test, solar irradiance was measured using a solar power meter, auxiliary gas energy input was recorded via a gas flow meter and energy conversion factor, and the system temperatures (T1, T2 & T3), current, and voltage were monitored and recorded using a data logger. To improve measurement reliability, all sensors were calibrated prior to the experimental tests. Although uncertainties related to temperature measurement, irradiance fluctuation, and turbine efficiency exist, the measurements provide a reasonable estimate of system performance for a prototype-scale experimental setup. Therefore, the designed considerations and assumptions of the fabricated system are summarized in Table 1.

Table 1: Design Considerations and Assumptions

Parameter	Symbol	Design Equation /Unit	Assumption/Calculated Value
Trough Length	L	___ [m]	4.00 m
Aperture Width	a	___ [m]	1.98 m
Parabolic Depth	d	___ [m]	0.61 m
Focal Length	f	$f = \frac{a^2}{16d}$ [m]	0.401 m
Receiver Radius	r_r	___ [m]	0.013 m
Receiver Diameter	D_r	$D_r = 2 \cdot r_r$ [m]	0.026 m
Rim Angle	ψ	$\tan\psi = \left(\frac{a}{f}\right) \cdot [2^{-1} - 8^{-1}\left(\frac{a}{f}\right)^{-2}]$ [°]	80 °
Collector Aperture Area	$A_{ap.c}$	$A_{ap.c} = a \cdot L$ [m²]	7.92 m²
Receiver Aperture Area	$A_{ap.r}$	$A_{ap.r} = 2\pi \cdot r_r \cdot L$ [m²]	0.33 m²
Concentration Ratio	C_G	$C_G = \frac{A_{ap.c}}{A_{ap.r}}$ [-]	24
Experiment Duration	___	___	Three (3) days in Ilorin, Nigeria

Parameter	Symbol	Design Equation /Unit	Assumption/Calculated Value
Specific Heat Capacity of Water	C_P	C_P = 4180 J/Kg ·K	4180 J/Kg ·K
Mass Flow Rate (Parabolic, 3-day average)	$\dot{m}_1$	$\dot{m}_1 = \frac{m}{t}$	4.51 x 10^{-8} Kg/s
Mass Flow Rate (Superheated, 3-day average)	$\dot{m}_2$	$\dot{m}_2 = \frac{m}{t}$	3.44 x 10^{-4} Kg/s
Receiver Temperature Difference (3-day average)	ΔT	ΔT = T2 - T1 [ºC]	57.83 ºC
Superheater Temperature Difference (3-day average)	ΔT	ΔT = T3 - T2 [ºC]	71.02 ºC
Useful Solar Thermal Energy Input (3-day average)	Q_{solar}	$Q_{solar} = C_p \cdot \dot{m}$ (T2 - T1) [Wh]	0.087 KWh
Auxiliary Gas Energy Input (3-day average)	Q_{gas}	Q_{total} - Q_{solar} [Wh]	0.012 KWh
Net useful electrical power Input (3-days average)	$P_{electric}$	$P_{electric}$ = I · V · t [W]	0.008 KWh
Total Energy Input (3-days average)	Q_{total}	$Q_{total} = \frac{Q_{useful}}{\eta_{overall}}$ [Wh]	0.099 KWh
Solar Contribution (3-days average)	C_{solar}	$C_{solar} = \frac{Q_{solar}}{Q_{solar}+Q_{gas}}$ [-]	0.88
Auxiliary Gas Contribution (3-days average)	C_{gas}	$C_{gas} = (1 - C_{solar})$ [-]	0.12
Overall System Efficiency (3-days average)	$\eta_{overall,avg}$	$\eta_{overall,avg} = \frac{\Sigma P_{electic}}{\Sigma Q_{solar}+Q_{gas}}$ x 100 [%]	7.90 %

Clarification of Design Parameters and Energy Calculations

The parameters presented in Table 1 summarize the main design considerations and calculated performance variables used for the hybrid solar thermal parabolic trough system. The geometric dimensions of the collector, including the trough length (4.0 m), aperture width (1.98 m), and parabolic depth (0.61 m), were obtained from the fabricated prototype structure. Using these measured dimensions, the focal length of the parabolic reflector was determined from the standard parabolic geometry relationship ($f = \frac{a^2}{16d}$), yielding a focal distance of approximately 0.401 m. This value ensured that the evacuated absorber tube was positioned accurately along the focal line of the trough for maximum solar energy concentration.

The collector aperture area was calculated as ($A_{ap.c}$= a · L), resulting in an aperture area of 7.92 m². The receiver aperture area was determined from the cylindrical surface area of the absorber tube, expressed as ($A_{ap.r} = 2\pi \cdot r_r \cdot L$), which yielded approximately 0.33 m². The geometric concentration ratio was therefore obtained from ($C_G = \frac{A_{ap,c}}{A_{ap,r}}$), giving a value of approximately 24. This value falls within the typical concentration ratio range reported for medium-scale parabolic trough collectors (Goswami & Kreith, 2017).

The average overall system efficiency was evaluated using the relationship:

$$\eta_{overall.avg} = \frac{\Sigma P_{electric}}{\Sigma Q_{solar}+ Q_{gas}} \text{ x } 100 \qquad (6)$$

Where:

$P_{electric}$ – represents the electrical energy generated by the DC generator,

Q_{solar} – is the useful thermal energy obtained from solar radiation

Q_{gas} – is the auxiliary thermal energy supplied by the gas burner.

Using the measured values (Q_{solar} = 0.087 kWh, Q_{gas} = 0.012 kWh, and $P_{electric}$ = 0.008 kWh), the average overall system efficiency of the prototype was approximately 7.9%. The higher value of about 26% reported in the results section corresponds to the Short-duration instantaneous peak efficiency performance observed during periods of high solar irradiance rather than the average electrical conversion efficiency of the entire system.

All measurements were obtained using calibrated instrumentation. Solar irradiance was measured using a solar power meter with an estimated uncertainty of ±5%, while temperature measurements were recorded using thermocouples with an accuracy of approximately ±1°C. Electrical measurements of voltage and current were taken using current and voltage sensors, respectively, with an estimated accuracy of ±0.5%. The combined

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uncertainty associated with the calculated efficiency values is therefore estimated to be within ± 5.1%.

The prototype system utilized a small impulse steam turbine coupled to a 0.065 kW DC generator. Due to its small scale, the mechanical-to-electrical conversion efficiency is expected to be below 30%, which partially explains the modest electrical output observed. In addition, typical thermal losses from the absorber tube, piping network, and superheater including convection and radiation can account for approximately 15–25% of the collected solar energy, even with insulation applied (Dincer & Rosen, 2010; Duffie & Beckman, 2013). Combined with optical losses (10–20%) and turbine-generator conversion losses (40–60%), these effects explain why the measured overall solar-to-electric efficiency falls within the expected 5–12% range for small-scale experimental PTC systems.

Figures 1, 2, and 3 show the system schematic diagram, experimental setup, and steam turbine electric generation room inner view, respectively.
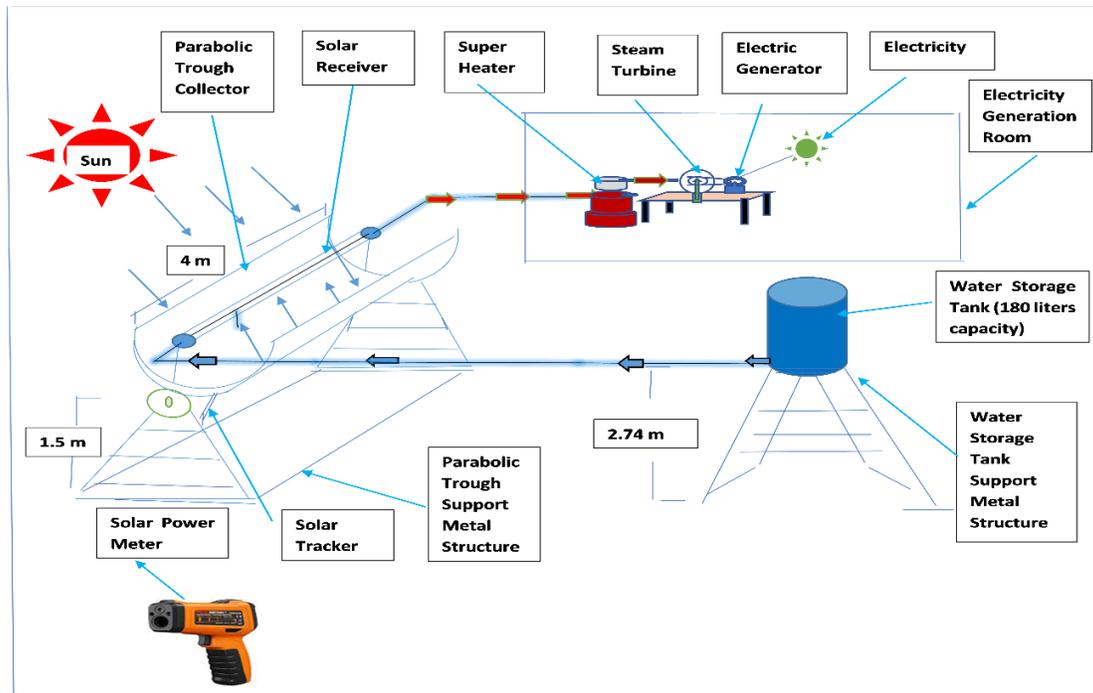
Figure 1: System schematic diagram
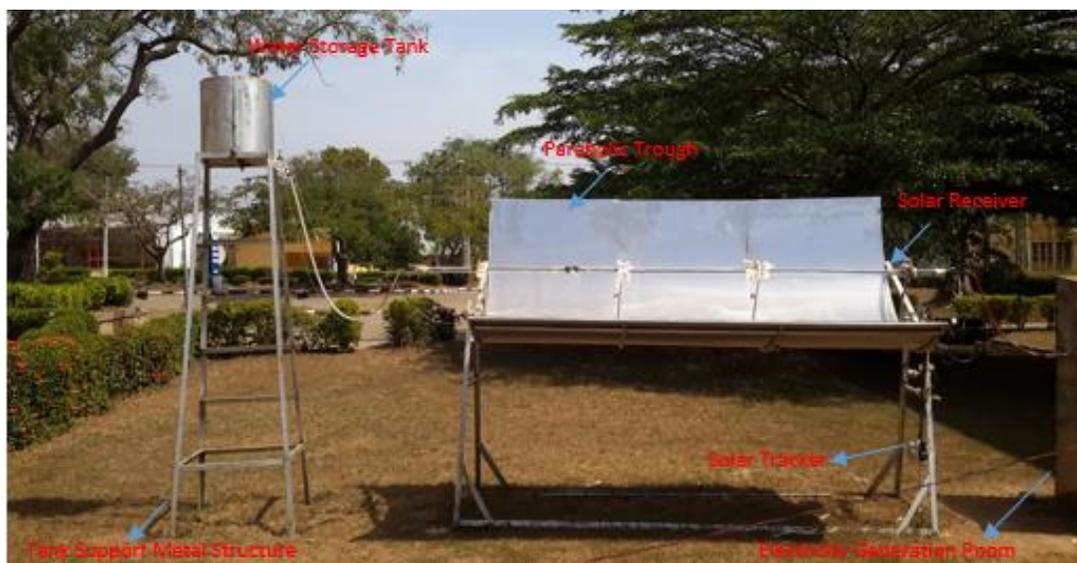
Figure 2: Experimental Setup
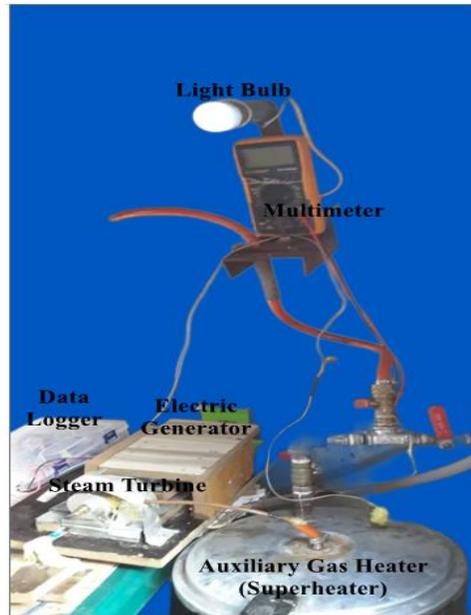
Figure 3: Steam turbine electric generation room inner view

RESULTS AND DISCUSSION

The experimental testing took place between the 9th and 11th of December 2019, from 9:00 AM to 5:00 PM, with measurements taken every 10 minutes. Significant parameters such as solar irradiance (Gd), receiver inlet and outlet temperatures (T1 and T2), superheater temperature (T3), generated power (P), and overall system efficiency were measured and assessed.

Day 1 Performance (December 9th, 2019)

On day one, the system testing began at 9:00 AM and ended at 5:00 PM, with measurements taken every 10 minutes. Figure 4 shows the daily solar irradiance patterns for day 1. Solar irradiance increased steadily from 9:00 AM, peaking at 1063 W/m² at 12:40 PM, before dropping due to occasional cloud cover and late-afternoon decline. The average irradiance during the day was 896.90 W/m². The fluctuations in the irradiance curve can be attributed to transient atmospheric disturbances such as partial cloudiness, which are visible in Ilorin meteorological records from December 2019 (FreeMeteo, 2019). Figure 5 shows the temperature profiles of the water inlet (T1), outlet (T2), and the superheater (T3). The three temperatures increased until around 2:50 PM, closely reflecting the solar irradiation trend. The highest recorded temperatures were 42.47 °C (T1), 163.20 °C (T2), and 277 °C (T3). The average temperatures were 37.00 °C (T1), 86.28 °C (T2), and 165.37 °C (T3). The close correlation between irradiance and thermal response is consistent with solar thermal system behavior reported in prior studies (Kalogirou, 2004).

Power generation, as shown in Figure 6, began effectively after 11:00 AM when steam temperatures reached the operational threshold. At 2:50 PM, the power reached a peak of 40.79 W with an average of 13.19 W. The delay is consistent with the system's thermal ineffectiveness. Figure 7 shows the system efficiency curve exhibited a similar pattern to the power output trend, increasing gradually as solar irradiance increased during the day. Short-duration peak efficiencies approaching 26.23% were observed during certain measurement intervals when electrical output temporarily increased while the estimated energy input remained relatively constant. However, when averaged over the entire experimental period, the overall solar-to-electric efficiency of the system was approximately 7.9%, which is consistent with the typical performance of small-scale prototype parabolic trough systems, where overall solar-to-electric efficiencies commonly range between 5% and 12% depending on collector design, turbine configuration, and operating conditions (Kalogirou, 2004; Padilla et al., 2011; Gunerhan & Hepbasli, 2007). The difference between peak and average efficiencies may be attributed to measurement fluctuations, transient thermal conditions within the receiver, and uncertainties associated with estimating the total energy input.
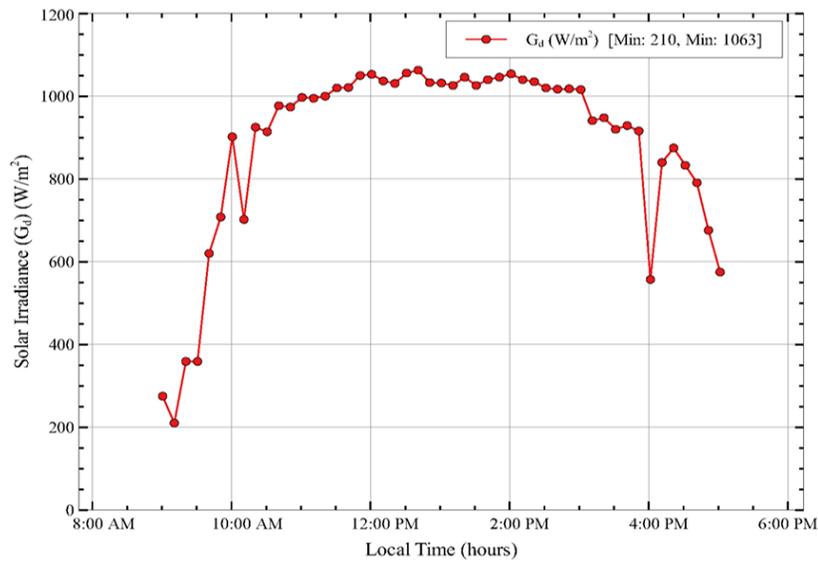
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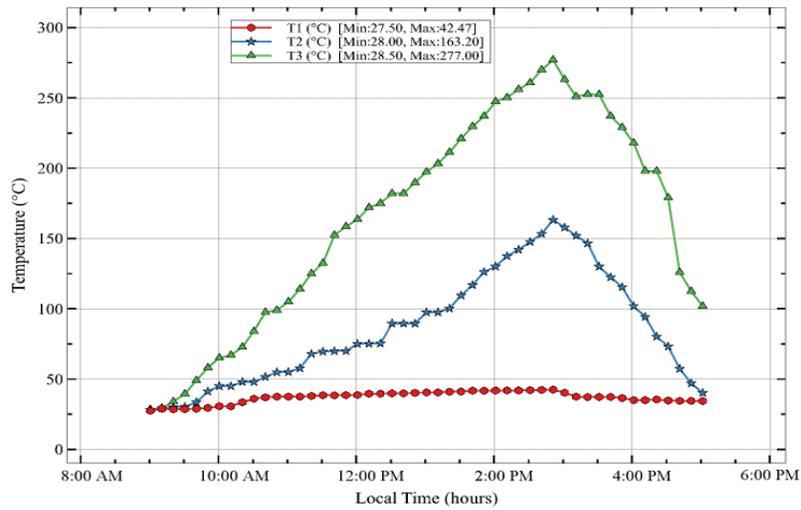Figure 4: Diurnal Variation of Solar Irradiance with Time for day 1

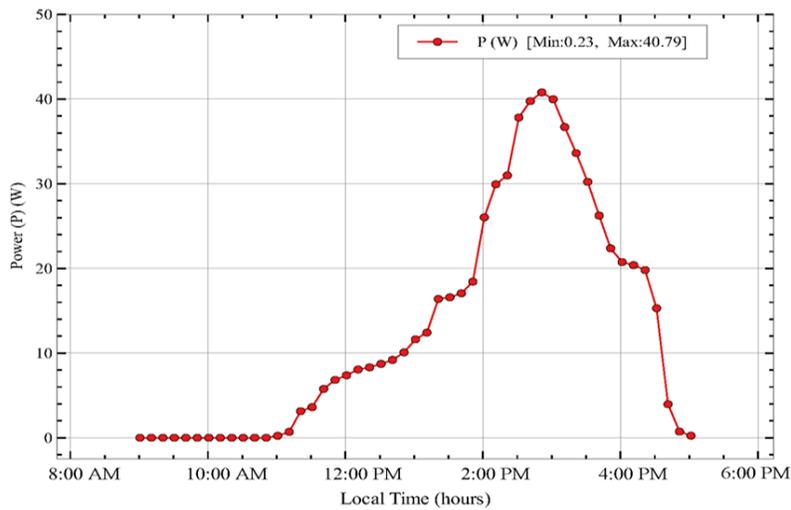Figure 5: Diurnal Variation of Temperatures with Time for day 1

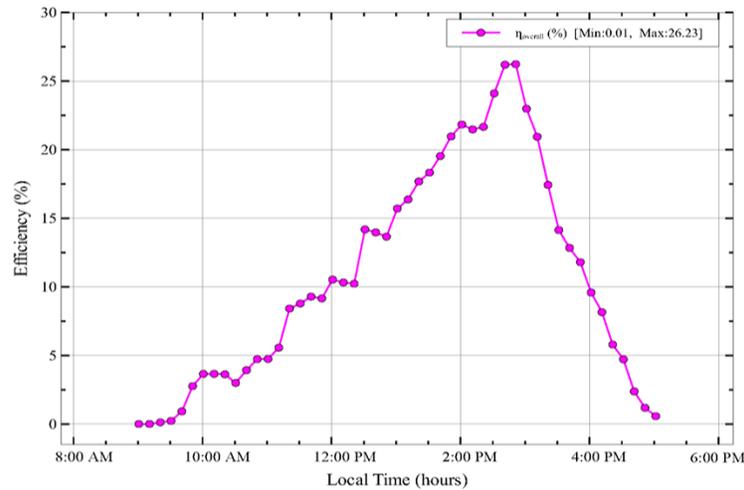Figure 6: Diurnal Variation of Power with Time for day 1

Figure 7: Diurnal Variation of Instantaneous Overall Efficiency with Time for day 1

Day 2 Performance (December 10th, 2019)

The same time and data-gathering procedure was used for the system testing on day 1. Day 2, saw a significant rise in solar irradiance, peaking at 1061 W/m² at 12: 30 PM (Figure 8). When compared to day 1, the average irradiance for the day was lesser, at 832.00 W/m². The lower average and intermittent behavior point to increased cloud cover or atmospheric haze (FreeMeteo, 2019). Figure 9 shows a midday peak, albeit at lower absolute values than day 1. Maximum readings were 38.20 °C (T1), 120.30 °C (T2), and 240.65 °C (T3), with average values of 33.16 °C, 61.56 °C, and 122.41 °C, respectively. This decline aligns with the slightly reduced solar input and validates the strong dependence of thermal performance on irradiance. The graph in Figure 10 indicates that power generation began after 12:00 PM and peaked at 24.41 W around 2:20 PM. The average power output of 4.42 W on day 2 was much lower than on day 1,

indicating both a reduced thermal gradient and a delayed operational start.

The system efficiency trend shown in Figure 11 followed the variation in power output and solar irradiance throughout the day. Short-duration peak efficiencies approaching 18.06% were observed during certain measurement intervals when electrical output temporarily increased while the estimated energy input remained relatively stable. However, when averaged over the entire experimental period, the overall solar-to-electric efficiency of the system was approximately 5.67%, reflecting the reduced thermal energy input and delayed steam generation caused by intermittent cloud cover and atmospheric disturbances. The lower average efficiency compared to day 1 is consistent with the reduced irradiance levels and weaker thermal gradients within the receiver system, which directly influence the steam generation process and electrical power output in small-scale solar thermal systems (Gunerhan & Hepbasli, 2007).
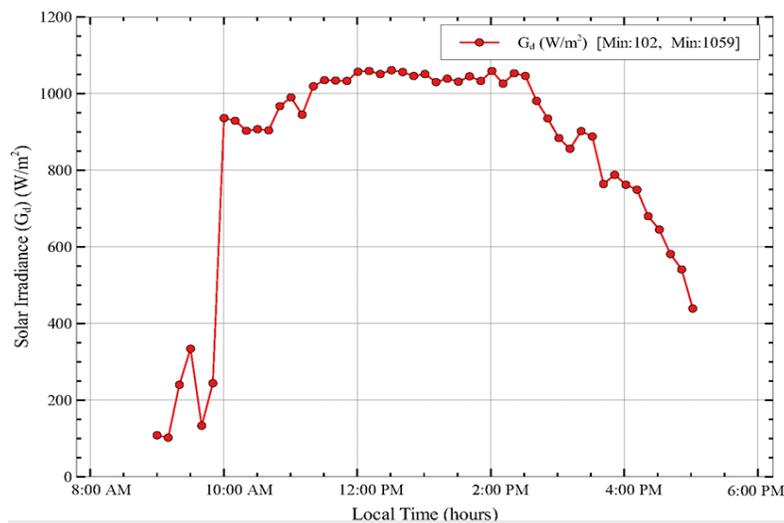

Figure 8: Diurnal Variation of Solar Irradiance with Time for day 2
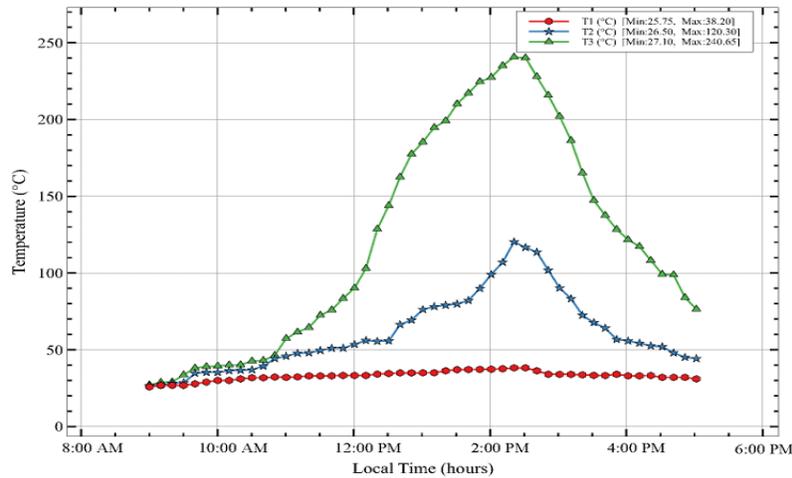
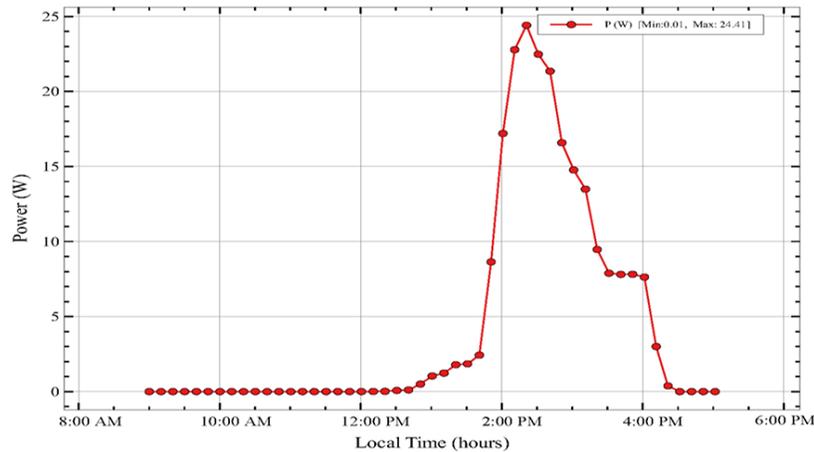Figure 9: Diurnal Variation of Temperatures with Time for day 2

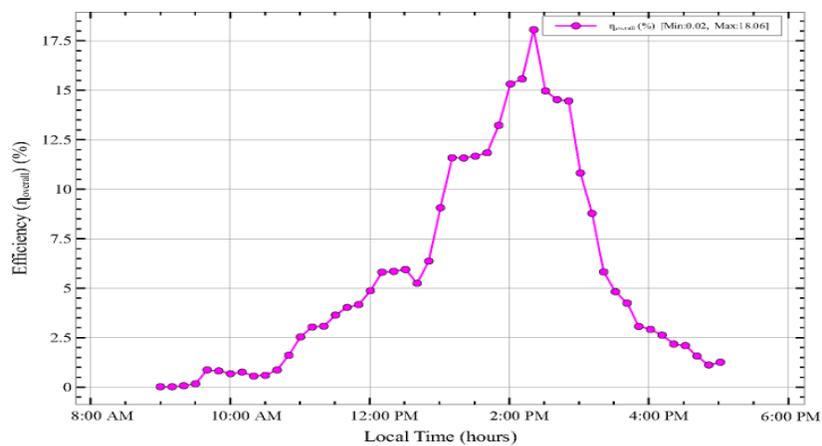Figure 10: Diurnal Variation of Power with Time for day 2

Figure 11: Diurnal Variation of Instantaneous Overall Efficiency with Time for day 2

Day 3 Performance (December 11ᵗʰ, 2019)

On day 3, the solar irradiance as disclosed in Figure 12 increased progressively until 1:10 PM, then declined gradually until 5:00 PM. A peak irradiance of 1066 W/m² was recorded at 2:20 PM, with an average daily value of 840.98 W/m² slightly better than day 2, though still lower than day 1.

Figure 13 shows that thermal responses followed the irradiance pattern. Temperatures peaked at 45.46 °C (T1), 132.64 °C (T2), and 235.50 °C (T3) at 2:10 PM and

averages at 35.57 °C, 73.55 °C, and 139.31 °C, respectively. The slightly higher inlet temperature compared to day 2 could be attributed to clearer morning conditions.

As per Figure 14, power output became significant only after 11:20 AM, peaking at 29.80 W at 2:10 PM. The average power obtained for day 3 was 5.72 W, which was better than day 2 but lower than day 1, reinforcing the sensitivity of the system to irradiance and steam generation thresholds. The efficiency trend presented in Figure 15 followed a pattern similar to the power generation curve, increasing gradually as solar irradiance and receiver temperatures increased during the afternoon

period. Short-duration peak efficiencies approaching 20.15% were recorded during certain measurement intervals when electrical output momentarily increased relative to the estimated energy input. However, when averaged over the full experimental period, the overall solar-to-electric efficiency of the system was approximately 7.22%. This average value reflects the combined effects of variable solar irradiance, transient thermal conditions within the receiver and superheater, and the limited energy conversion capability of the small impulse turbine and generator used in the prototype system.
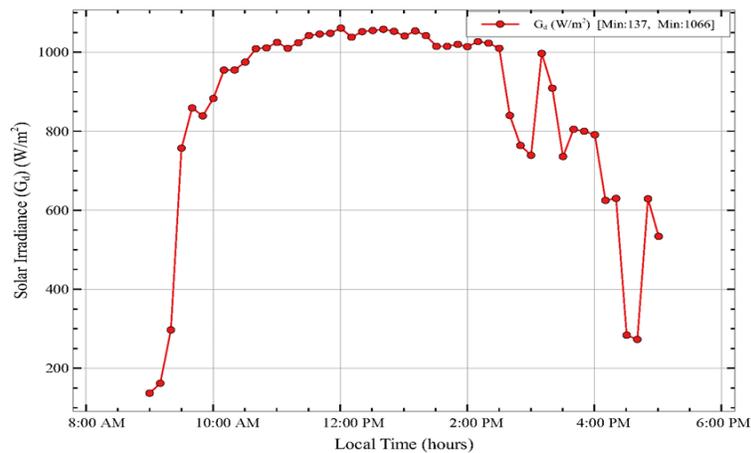

Figure 12: Diurnal Variation of Solar Irradiance with Time for day 3
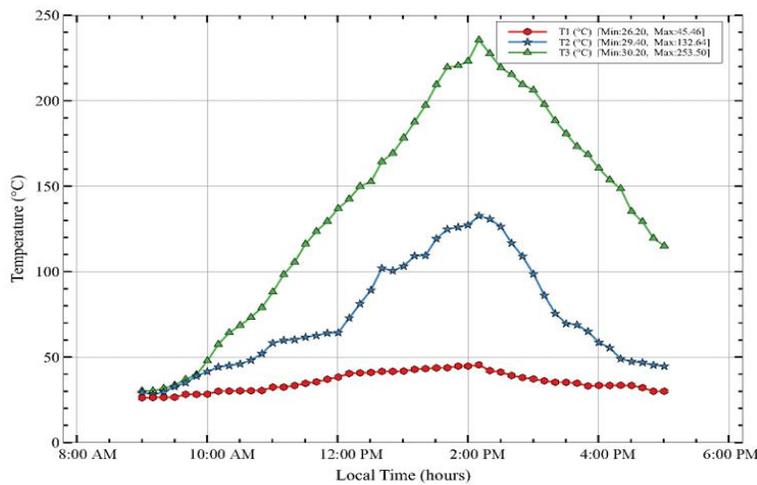

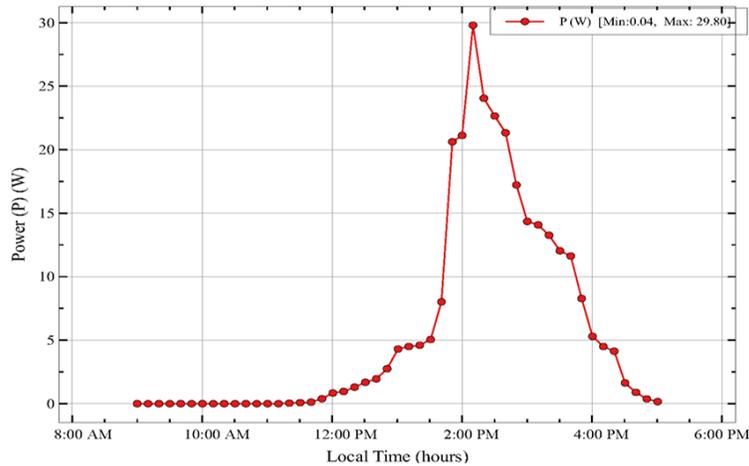Figure 13: Diurnal Variation of Temperatures with Time for day 3

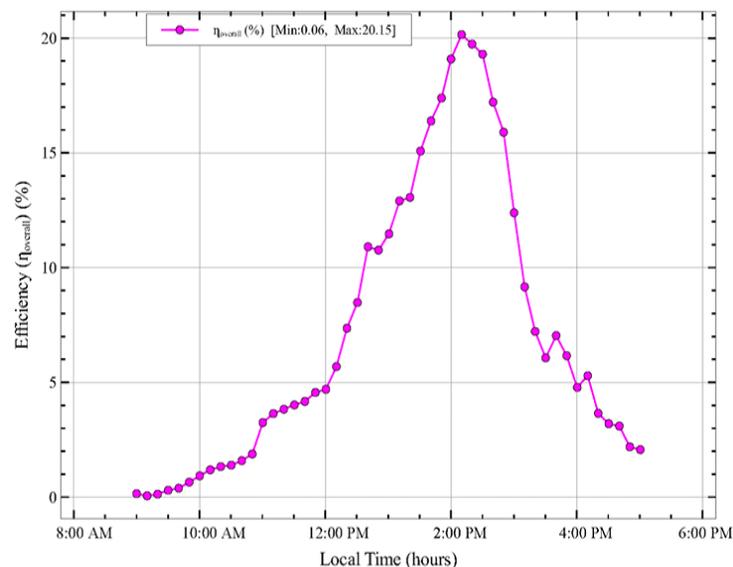Figure 14: Diurnal Variation of Power with Time for day 3

Figure 15: Diurnal Variation of Instantaneous Overall Efficiency with Time for day 3

In practical solar thermal power systems, several forms of energy losses occur during energy conversion, including optical losses from mirror reflectivity and tracking inaccuracies, thermal losses from the absorber tube and piping through convection and radiation, and mechanical/electrical losses in the turbine-generator assembly. Based on values reported in the literature for prototype-scale parabolic trough systems, optical losses typically range from 10–20%, thermal losses from convection and radiation account for 15–25%, and mechanical/electrical conversion losses for small impulse turbines and DC generators can reach 40–60% (Duffie & Beckman, 2013; Kalogirou, 2014; Lovegrove & Stein, 2012). These combined losses explain why the overall solar-to-electric efficiency of small experimental PTC systems generally falls within 5–12%, which is consistent with the average efficiency measured in the present study.

Comparative Efficiency Evaluation
Figure 16 illustrates the variation of system efficiency ($\eta_{overall}$) with time for three experimental days (December 9th, 10th, and 11th, 2019) in the performance evaluation of the hybrid solar thermal parabolic trough power generation system with auxiliary gas support.
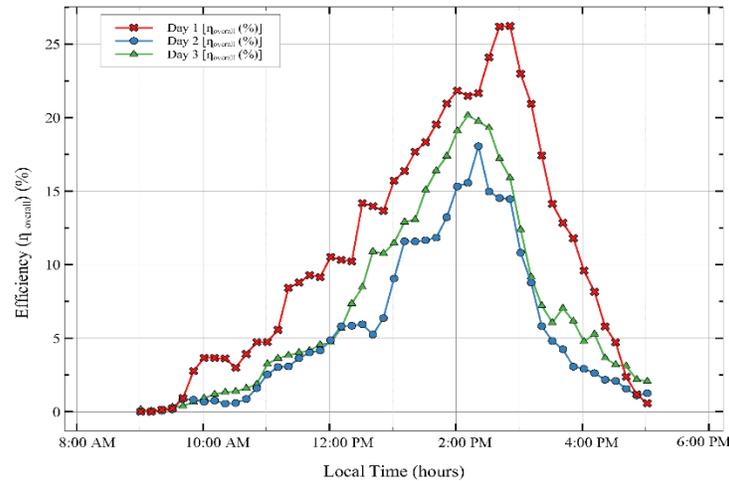
Figure 16: Variation of System Instantaneous Efficiency ($\eta_{overall}$) with Time for days 1 to 3

The diurnal pattern in the system instantaneous efficiency with time over the three days is shown in the results displayed in Figure 16. Due to a decrease in solar irradiance, the efficiency was particularly low in the early morning (9:00 - 9:30 AM), increased progressively to peak values between 2:30 and 3:00 PM, and then declined toward the end of the afternoon.

On day 1 (December 9th, 2019), the system achieved the maximum instantaneous efficiency of 26.23% at approximately 2:50 PM, coinciding with near-zenith solar position and favorable thermal conditions in the collector. However, this value represents a transient peak rather than sustained performance. The daily average efficiency for day 1 was 7.9%, which aligns with typical small-scale prototype PTC performance. This observation is consistent with previous research showing that parabolic trough systems produce maximum thermal-electric conversion around solar noon under clear-sky conditions (Kalogirou, 2004; Hassain et al., 2018).

On day 2 (December 10th, 2019), peak instantaneous efficiency was 18.06% at 2:20 PM, lower than day 1, likely due to cloud cover and atmospheric attenuation. The daily average efficiency was 5.67%, reflecting reduced thermal energy input and delayed steam generation under less favorable solar conditions. The smoother efficiency curve suggests slightly lower operating losses on this day, as reported in comparable hybrid solar-gas thermal systems (Kumar & Rosen, 2011).

Day 3 (December 11th, 2019) saw a peak instantaneous efficiency of 20.15% at 2:10 PM, while the daily average efficiency was 7.22%. The slightly higher peak compared to day 2 reflects clearer morning conditions and better solar irradiance. Efficiency remained below 1% before 10:00 AM on all three days because the receiver had not reached operational temperature, even when the auxiliary gas burner was activated, highlighting the importance of

hybridization for low-radiation periods (Dincer & Rosen, 2010).

From 12:00 PM to 2:30 PM, the system maintained efficiencies between 14% and 26%, indicating thermal saturation at peak solar intensity. Decreases in efficiency after 3:00 PM correspond to declining solar irradiance and reduced capacity to generate high-temperature steam. These trends are consistent with literature showing that optical losses, low-angle insolation, and transient thermal conditions reduce performance after solar zenith (Padilla et al., 2011).

Across all three days, the average overall solar-to-electric efficiency of the hybrid system ranged between 5.67% and 7.9%, consistent with reported values for experimental small-scale parabolic trough systems (Kalogirou, 2004; Padilla et al., 2011; Gunerhan & Hepbasli, 2007). The results in this study also indicate that the solar trough contributed the majority of the system's thermal input, while the auxiliary LPG burner mainly supported startup and low-radiation periods. Although the gas input had limited impact on peak efficiency, it played a critical role in maintaining operational stability. These observations are in line with previous studies emphasizing the importance of optimizing hybrid solar-gas systems for off-grid or intermittent grid-connected applications (Rajaei et al., 2016; Vakilabadi et al., 2019). While detailed statistical analysis such as error bars or sensitivity analysis was beyond the scope of this prototype study, the combined measurement uncertainty of ±5.1% provides a reasonable estimate of reliability for the calculated efficiency values.

CONCLUSION

This study successfully demonstrated the design, fabrication, and performance evaluation of a hybrid solar thermal parabolic trough system adapted for power generation in Nigeria's climatic conditions. The system incorporated a locally constructed parabolic trough

collector using acrylic mirror sheets, a borosilicate glass solar receiver, a single-axis solar tracking device, and a superheated steam turbine generator supported by a liquefied petroleum gas (LPG) burner as an auxiliary heat source.

The experimental results for the three days of testing indicate a high dependency of system operation on the solar radiation received. The first day of testing under high solar irradiance produced the highest electrical output of 40.79 W. Short-duration instantaneous peak efficiency values approaching 26.23% were observed during certain measurement intervals; however, when averaged over the entire experimental period, the overall solar-to-electric efficiency of the system was approximately 7.9%, which is consistent with the typical performance of small-scale prototype parabolic trough systems, indicating that the system is capable of converting solar irradiance into sustained power regardless of weather conditions. Average efficiencies across the various test days were high as well, which further substantiated the robustness and applicability of the hybrid design. The local materials employed and the conventional construction processes are additional measures indicative of their economic and technical relevance for decentralized applications, such as rural and semi-urban un-electrified areas.

The addition of supplementary LPG heating has overcome the problem of the intermittent nature of solar thermal systems. While the gas burner contributed little to peak efficiency, it was essential for maintaining system output during early morning and late afternoon, or even under variable solar conditions. This hybrid scheme makes solar-thermal systems more competitive in areas of variable sunlight availability by allowing for steady and constant power generation (Vakilabadi et al., 2019).

The findings of this study are consistent with global efforts toward decarbonization and the United Nations Sustainable Development Goals (SDGs), in particular SDGs 7 on affordable and clean energy, and SDG 13 on climate action (United Nations Department of Economic and Social Affairs, 2020). It also supports local employment, and technological capability creation and achieves reduced environmental impact by also reducing the reliance on diesel and coal-fired generators.

Despite the study's achievements, more work needs to be done to enhance the overall performance and dependability of the system. While the hybrid solar thermal parabolic trough system demonstrated the feasibility of small-scale off-grid electricity generation, the overall electrical efficiency was constrained by the low capacity of the small impulse turbine, thermal losses in the receiver and piping, and the use of water as the heat transfer fluid. Future work should focus on improving insulation, exploring higher-temperature heat transfer fluids, and considering alternative power cycles such as organic Rankine cycles (ORC) to enhance electrical output. Incorporating detailed uncertainty analysis, better instrumentation, and optimized hybrid configurations could further refine system performance and reliability. These improvements will contribute to advancing sustainable solar thermal solutions aligned with energy access and climate-related Sustainable Development Goals (SDGs). This includes focusing more on the system's thermal insulation and energy losses, implementing automation control to maximize efficiency in real-time, and expanding the current prototype to produce more power. Furthermore, as noted by Okonkwo et al. (2021), advanced materials and nanofluid-based heat transfer may be investigated to improve the system's efficiency in various solar conditions.

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