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# Optimization of Solar Water Heating Systems for Enhanced Energy Efficiency Using Taguchi and Design of Experiments Methods

Abdulrahman DAUDA[1*], Kafayat O. ADEYEMI[2], Musa T. ZARMAI[3]

[1*]*Nigerian Railway Corporation, Abuja, Nigeria*
[2,3]*Department of Mechanical Engineering, University of Abuja, Abuja, Nigeria*

[1*]*abdulbaaba@yahoo.com*, [2]*kafayat.adeyemi@uniabuja.edu.ng*, [3]*musa.zarmai@uniabuja.edu.ng*

***Abstract***
*Due to unreliable electricity supply in North-Central Nigeria, optimizing solar water heating (SWH) systems is critical to enhancing domestic energy efficiency and meeting household hot water needs. This study was motivated by the need to address inconsistent hot water availability and reduce dependence on fossil fuel-based heating. By acquiring and analyzing performance data from existing systems, the research employs advanced simulation tools, including MATLAB, to evaluate key design parameters such as collector area, insulation thickness, tilt angle, and flow rate. Using the Taguchi optimization method and Design of Experiments (DOE), the study systematically explores the impact of these factors on system performance. The results reveal significant improvements, with optimized systems achieving a consistent thermal efficiency of 60%, compared to baseline efficiencies ranging from 5% to 70%, depending on time of day and climatic conditions. Optimal settings included a collector area of 0.95 m², tilt angle of 25.5°, and a flow rate of 0.17 m/s, with outlet temperatures 2.5–4 °C higher than baseline models. Energy output increased by an average of 35% over the tested time series. These gains demonstrate the potential for energy savings and reduced greenhouse gas emissions, underscoring the importance of robust design parameters and providing actionable insights for improving SWH systems for widespread adoption in Nigeria. This research contributes to the growing body of knowledge on renewable energy solutions, offering a pathway for sustainable energy use in households.*

***Keywords:*** *Solar water heating (SWH), optimization, Taguchi Method, energy efficiency, Design of Experiments.*

## 1. Introduction

This study aims to utilize MATLAB simulation, coupled with design of experiment (DOE) method to identify the optimal combination of flow rate, collector area, insulation thickness, and tilt angle that maximizes outlet temperature and energy output, as well as to analyze the thermal performance of a thermosyphon solar water heater. Solar water heating (SWH) systems have emerged as an effective and sustainable alternative to conventional water heating methods, such as electric and gas water heaters. These systems utilize solar energy to heat water, reducing reliance on fossil fuels and contributing to lower greenhouse gas emissions. The growing demand for renewable energy solutions, followed by the increasing cost of electricity, has heightened interest in optimizing SWH system performance (Patel, 2023).

Numerous studies have explored the design, modeling, simulation, and optimization of SWH systems, demonstrating their potential as a viable alternative to conventional water heaters. Patel (2023) provides a comprehensive review outlining various design strategies and performance metrics for SWH systems, illustrating how they have evolved into commercially viable and efficient solutions for residential and institutional applications. Similarly, Kchaou (2024) investigates advanced design improvements incorporating Phase Change Materials (PCMs), heat pipes, and turbulators, highlighting how these components enhance thermal efficiency and cost savings, particularly during peak operational periods.

Further advancements in SWH system design and optimization have been made by Anand and Patel (2023), who emphasize the importance of dynamic sizing to accommodate variable water demand patterns. Their study applies optimization techniques, such as genetic algorithms and particle swarm optimization, to tailor system configurations to local climatic conditions, improving both energy efficiency and economic feasibility. Yaman and Arslan (2018) explore the impact of seasonal climate variations on system performance, finding that optimally aligning parameters like collector area and storage tank volume with regional weather patterns enhances overall efficiency while reducing life cycle costs.

Additional research utilizing TRNSYS simulations has provided valuable insights into natural and forced circulation configurations, demonstrating that increasing collector area and water tank volume improves efficiency below certain thresholds (Yan et al., 2021). Al Zurfi et al. (2024) further investigate efficiency improvements in flat-plate collectors by strategically integrating PCMs, leading to prolonged heating periods and enhanced performance during low solar irradiation.

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Despite these technological advancements, the adoption of SWH systems in Nigeria remains limited due to inefficiencies in design, high initial investment costs, and a lack of awareness regarding their long-term economic and environmental benefits. Furthermore, factors such as collector tilt angle, insulation thickness, and storage tank capacity significantly influence thermal efficiency and overall energy output.

To address these challenges, this study employs a systematic approach using Design of Experiments (DOE) and the Taguchi method to optimize SWH system performance. By identifying the most effective combination of design parameters, specifically collector area, tilt angle, and flow rate, the study aims to enhance energy efficiency, improve thermal output, and reduce energy losses. The findings contribute to ongoing research on sustainable energy solutions by demonstrating how advanced optimization techniques can significantly improve SWH system performance in Nigerian conditions.

## 2. Materials and Method

### 2.1 Data and Factors for Simulation and Optimization

This study employs a Design of Experiments (DOE) approach, integrating MATLAB-based simulations to optimize solar water heating systems (Antony, 2014; Phadke, 1989). Key performance metrics include thermal efficiency, energy output, and outlet temperature (Duffie & Beckman, 2013).

Table 1 presents compiled performance data from field studies of a thermosyphon SWH system (Uwah, 2020). This data forms the baseline for developing the MATLAB simulation model used in this research.

### 2.2 Identification of Key Factors

A thermosyphon SWH model was developed and simulated in MATLAB using time-series performance data derived from Table 1 (Uwah, 2020; Sopian et al., 2009).

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Table 1: Performance data from existing solar water heater (SWH) system (Uwah, 2020)

| Parameter | Value | Material |
|---|---|---|
| Collector Area | 0.76m^2 | |
| Collector Casing Insulation | 0.025m | Styrofoam |
| Volume of heated water | 0.036m^3 | |
| Flow Velocity (Maximum allowable = 0.6m/s) | 0.1m/s | |
| Flow chanel diameter | 0.0127m | |
| Absober plate Inclination Angle | 7 degrees | |
| Absorber plate absorptivity(Plain black Paint coating) | 0.7 | Aluminium |
| Cover material Transmittance | 0.9 | White glass |
| Riser Thermal conductivity | 385W/mK | Copper |
| Absorber plate Thermal conductivity | 225W/mK | Aluminium |
| Insulating material Thermal Conductivity (0.02m) | 0.04W/mK | Fibre glass |

| Day 01 | | | | | |
|---|---|---|---|---|---|
| Date/Time | Ambient Temp. (°C) | Inlet Temp. (°C) | Outlet Temp.(°C) | Irradiance (W/m^2) | Efficiency (%) |
| 23-09-20/10:00AM | 25.00 | 25.00 | 27.00 | 565.00 | 4.89 |
| 23-09-20/11:00AM | 27.00 | 30.00 | 30.50 | 603.00 | 1.15 |
| 23-09-20/12:00PM | 28.00 | 30.00 | 31.10 | 704.00 | 2.16 |
| 23-09-20/13:00PM | 28.00 | 30.00 | 50.00 | 826.00 | 33.45 |
| 23-09-20/14:00PM | 28.00 | 32.00 | 65.00 | 681.00 | 66.95 |
| 23-09-20/15:00PM | 29.00 | 30.00 | 37.00 | 543.00 | 17.81 |

| Day 02 | | | | | |
|---|---|---|---|---|---|
| Date/Time | Ambient Temp. (°C) | Inlet Temp. (°C) | Outlet Temp.(°C) | Irradiance (W/m^2) | Efficiency (%) |
| 25-09-20/10:00AM | 26.00 | 26.00 | 28.00 | 519.00 | 5.32 |
| 25-09-20/11:00AM | 26.00 | 26.00 | 46.80 | 604.00 | 47.58 |
| 25-09-20/12:00PM | 27.00 | 27.00 | 53.00 | 615.00 | 58.41 |
| 25-09-20/13:00PM | 28.00 | 27.00 | 50.10 | 749.00 | 42.61 |
| 25-09-20/14:00PM | 27.00 | 30.00 | 61.00 | 683.00 | 62.71 |
| 25-09-20/15:00PM | 27.00 | 32.00 | 53.80 | 493.00 | 61.09 |

| Day 03 | | | | | |
|---|---|---|---|---|---|
| Date/Time | Ambient Temp. (°C) | Inlet Temp. (°C) | Outlet Temp.(°C) | Irradiance (W/m^2) | Efficiency (%) |
| 01-10-20/10:00AM | 25.00 | 24.10 | 24.80 | 374.00 | 2.59 |
| 01-10-20/11:00AM | 26.00 | 24.50 | 42.10 | 373.00 | 65.19 |
| 01-10-20/12:00PM | 27.00 | 25.70 | 48.50 | 541.00 | 58.23 |
| 01-10-20/13:00PM | 28.00 | 27.40 | 57.10 | 621.00 | 66.08 |
| 01-10-20/14:00PM | 28.00 | 29.30 | 53.00 | 599.00 | 54.66 |
| 01-10-20/15:00PM | 28.00 | 32.00 | 50.10 | 563.00 | 44.42 |

| Day 04 | | | | | |
|---|---|---|---|---|---|
| Date/Time | Ambient Temp. (°C) | Inlet Temp. (°C) | Outlet Temp.(°C) | Irradiance (W/m^2) | Efficiency (%) |
| 28-10-20/10:00AM | 29.00 | 28.80 | 30.30 | 805.00 | 2.57 |
| 28-10-20/11:00AM | 30.00 | 29.70 | 50.10 | 908.00 | 31.04 |
| 28-10-20/12:00PM | 32.00 | 31.50 | 77.40 | 930.00 | 68.19 |
| 28-10-20/13:00PM | 33.00 | 36.70 | 74.50 | 868.00 | 60.17 |
| 28-10-20/14:00PM | 33.00 | 42.90 | 70.80 | 731.00 | 52.73 |
| 28-10-20/15:00PM | 33.00 | 45.10 | 63.30 | 531.00 | 47.35 |

| Day 05 | | | | | |
|---|---|---|---|---|---|
| Date/Time | Ambient Temp. (°C) | Inlet Temp. (°C) | Outlet Temp.(°C) | Irradiance (W/m^2) | Efficiency (%) |
| 29-10-20/10:00AM | 29.00 | 30.10 | 31.50 | 824.00 | 2.35 |
| 29-10-20/11:00AM | 29.00 | 34.30 | 53.10 | 903.00 | 28.76 |
| 29-10-20/12:00PM | 31.00 | 37.80 | 76.00 | 903.00 | 58.45 |
| 29-10-20/13:00PM | 32.00 | 43.60 | 64.50 | 823.00 | 35.09 |
| 29-10-20/14:00PM | 32.00 | 46.50 | 60.30 | 671.00 | 28.41 |
| 29-10-20/15:00PM | 32.00 | 46.70 | 55.60 | 460.00 | 26.73 |

| Day 06 | | | | | |
|---|---|---|---|---|---|
| Date/Time | Ambient Temp. (°C) | Inlet Temp. (°C) | Outlet Temp.(°C) | Irradiance (W/m^2) | Efficiency (%) |
| 30-10-20/10:00AM | 30.00 | 35.00 | 33.20 | 816.00 | 4.57 |
| 30-10-20/11:00AM | 30.00 | 31.70 | 59.80 | 916.00 | 42.38 |
| 30-10-20/12:00PM | 32.00 | 34..2 | 79.30 | 940.00 | 66.29 |
| 30-10-20/13:00PM | 33.00 | 39.80 | 73.50 | 884.00 | 52.67 |
| 30-10-20/14:00PM | 34.00 | 40.10 | 65.70 | 750.00 | 47.16 |
| 30-10-20/15:00PM | 34.00 | 43.40 | 60.20 | 551.00 | 42.12 |

Table 2 outlines the modeled input factors and simulation parameters used during the Taguchi experiment phase.

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Table 2: Factors and range for optimization

| Parameter | Symbol | Range | Unit |
|---|---|---|---|
| Collector Area | $A_c$ | 0.5 – 1.2 | $m^2$ |
| Collector Tilt Angle | $\theta$ | 1° – 50° | Degrees |
| Flow Rate | $Q_f$ | 0.05 – 0.6 | $m/s$ |
| Insulation Thickness (Casing) | $I_c$ | 0.01 – 0.10 | $m$ |
| Insulation Thickness (Tank) | $I_t$ | 0.01 – 0.10 | $m$ |
| Storage Tank Volume | $V_t$ | 0.036 – 0.09 | $m^3$ |
| Flow Channel Diameter | $D_f$ | 0.005 – 0.03 | $m$ |
| Absorber Plate Absorptivity | $\alpha$ | 0.7 – 0.95 | - |

In MATLAB, these were initialized using vectors:

```matlab
Ac = linspace(0.5, 1.2, 15);  % Collector area
theta = linspace(1, 50, 15);   % Tilt angle
Qf = linspace(0.05, 0.6, 15);  % Flow rate
Ic = linspace(0.01, 0.10, 15); % Insulation (casing)
It = linspace(0.01, 0.10, 15); % Insulation (tank)
Vt = linspace(0.036, 0.09, 15); % Storage tank volume
Df = linspace(0.005, 0.03, 15); % Flow channel diameter
alpha = linspace(0.7, 0.95, 15); % Absorber plate absorptivity
```

Each parameter was discretized into 15 levels using linspace(), enabling uniform resolution of factor levels (MathWorks, 2022)

**2.3 Design of Experiments (DOE)**

A Latin Hypercube Sampling (LHS) approach was employed to generate 15-level experimental configurations, ensuring broad coverage of design parameters (McKay et al., 1979). The Taguchi method was used to analyze signal-to-noise (S/N) ratios, optimizing for maximum thermal efficiency (Phadke, 1989).

```matlab
numFactors = 8; % Total number of design factors
numExperiments = 15; % Number of levels per factor
DOE_matrix = lhsdesign(numExperiments, numFactors); % Generate DOE matrix
```

This matrix ensured that each experiment sampled different parameter combinations, preventing clustering around specific values.

**2.4 Simulation Model Development**

Performance metrics were computed using energy balance equations:

- Absorbed Power ($P_{abs}$) (Duffie & Beckman, 2013):

$$P_{\text{abs}} = A_c \times I \times \tau \times \alpha \times \cos(\theta) \quad (1)$$

Where;

- $A_c$ = Collector area ($m^2$)
- I = Solar irradiance ($W/m^2$)
- τ = Transmittance of the collector cover

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- $a$ = Absorber plate absorptivity
- θ = Collector tilt angle (degrees)

```matlab
P_abs = Ac .* I .* tau .* alpha .* cosd(theta);
```

- Useful Power ($P_{useful}$) (Kalogirou, 2004):

$$P_{\text{useful}} = P_{\text{abs}} \times F_{\text{ins}} \quad (2)$$

Where;

- $F_{ins}$ = Normalized insulation factor (accounts for collector casing and tank insulation)

```matlab
P_useful = P_abs .* F_ins;
```

- Thermal Efficiency (η) (Duffie & Beckman, 2013):

$$\eta = \left[ \frac{P_{\text{useful}}}{(A_c \times I)} \right] \times 100 \quad (3)$$

```matlab
eta = (P_useful ./ (Ac .* I)) * 100;
```

- Energy Output (E) (ISO 9459-2, 1995):

$$E = P_{\text{useful}} \times t \quad (4)$$

Where;

- t = Time period (s)

```matlab
E_output = P_useful * 3600; % Energy output over 1 hour
```

- Temperature Rise (ΔT) (Duffie & Beckman, 2013):

$$\Delta T = \frac{E}{(m \times c)} \quad (5)$$

Where;

- m = Mass of water in the storage tank (kg)
- c = Specific heat capacity of water (J/kg·°C)

```matlab
delta_T = E_output ./ (m * c);
```

- Outlet Temperature ($T_{out}$) (Kalogirou, 2004):

$$T_{\text{out}} = T_{\text{in}} + \Delta T \quad (6)$$

Where;

- $T_{in}$ = Inlet temperature (°C)

```matlab
T_out = T_in + delta_T;
```

**2.5 Taguchi Optimization Process**

For each time step:

1. DOE Experiments Run: Simulated performance metrics computed for each experiment.
2. Signal-to-Noise (S/N) Ratio Calculation: The "larger-is-better" formula was used to maximize efficiency (Phadke, 1989).

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$$\text{SNR} = -10\log_{10}\left[\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right] \tag{7}$$

Where;

- $y_i$ represents the observed output values.
- n is the total number of observations.

```matlab
SN_ratio = -10 * log10(mean(1 ./ (E_output .^ 2), 2));
```

3. Optimal Factor Selection: The factor combination yielding the highest S/N ratio was identified and applied to compute optimized efficiency, energy output, and outlet temperature (Antony, 2014).

```matlab
[~, optIndex] = max(SN_ratio);
optParams = DOE_matrix(optIndex, :);
```

### 2.6 Simulation Visualization

To compare measured vs. optimized performance, MATLAB plots were generated using time-series efficiency data from Uwah (2020) and MathWorks (2022):

```matlab
figure;
plot(time, eta_measured, 'r--', 'LineWidth', 2); % Measured Efficiency
hold on;
plot(time, eta_DOE, 'ko-', 'LineWidth', 1.5); % DOE Experiments
plot(time, eta_optimized, 'b-', 'LineWidth', 2); % Optimized Efficiency
xlabel('Time of Day');
ylabel('Efficiency (%)');
legend('Measured', 'DOE Experiments', 'Optimized');
title('Solar Water Heater Efficiency Optimization');
grid on;
```

- Red Dashed Line: Measured efficiency
- Black Circles: DOE experimental efficiencies
- Blue Solid Line: Optimized efficiency (Taguchi method)

## 3. Results and Discussion

### 3.1 Solar Water Heater Simulation and Optimization Results

The MATLAB-based simulations provided a comparative analysis of measured vs. optimized performance across multiple time steps (10:00 AM – 3:00 PM). Figure 1 illustrates this comparison, showing that measured efficiency started at 5–10% in the morning, peaked at around 65% at midday, and declined toward 3:00 PM. Optimized efficiency, in contrast, maintained a stable 55–60% throughout the day. These results align with Sopian et al. (2009) and Aremu et al. (2020), who also reported peak efficiencies in the 60–70% range under similar climatic conditions.

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### 3.2 Efficiency Optimization Results

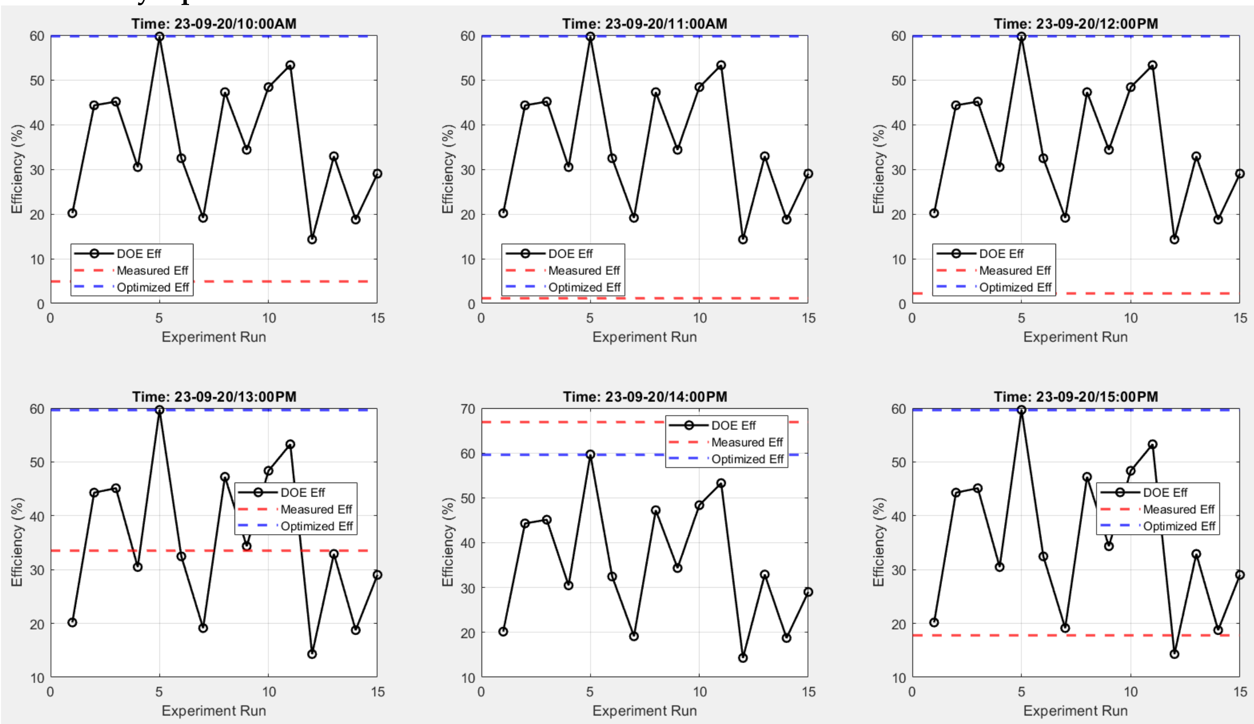


Figure 1: Chart of efficiency against time steps

#### 3.2.1 General observations

- Measured Efficiency (Red Dashed Line): Low in the morning (5-10%) but peaks around midday (60-70%) due to improved solar conditions.
- DOE Experiments (Black Curve): Efficiency varies significantly across runs (15-65%), emphasizing the impact of design parameters.
- Optimized Efficiency (Blue Dashed Line): Remains consistently high (55–60%), validating the effectiveness of the Taguchi optimization, similar to findings by Zhang et al. (2022) in high-insolation regions.

#### 3.2.2 Time-step insights

- 10:00 AM & 11:00 AM: Low measured efficiency due to suboptimal solar incidence; DOE experiments show potential for 40–50% efficiency with better parameter tuning. Comparable improvements were reported by Othman et al. (2017), confirming the role of early-day optimization in boosting thermal capture.
- 12:00 PM: Increased efficiency (about 10%), but optimized settings suggest a potential 3–6 times improvement over measured results in agreement with Yan et al. (2021) for TRNSYS-simulated SWH systems.
- 1:00 PM – 2:00 PM: Measured efficiency peaks (30–70%), DOE runs vary widely, and optimized settings remain near 60% consistent with trends reported by Fudholi et al. (2015).
- 3:00 PM: Performance drops, but optimized efficiency remains stable, indicating room for improvement in real-world conditions similar to the late-afternoon stabilization patterns observed by Kalogirou (2004).

#### 3.2.3 Key insights

- Design Sensitivity: Small changes in collector area, tilt angle, and insulation can significantly affect efficiency.
- Optimization Potential: Theoretical efficiency (60%) highlights opportunities for better design and control strategies.
- Real-World Variability: Practical constraints like shading, system transients, and operational losses cause deviations from the optimized model. This trend mirrors deviations noted by El-Khawajah et al. (2021) in field-based SWH performance assessments.

Figure 2 below shows the differences in efficiencies achieved between measured and optimized systems.

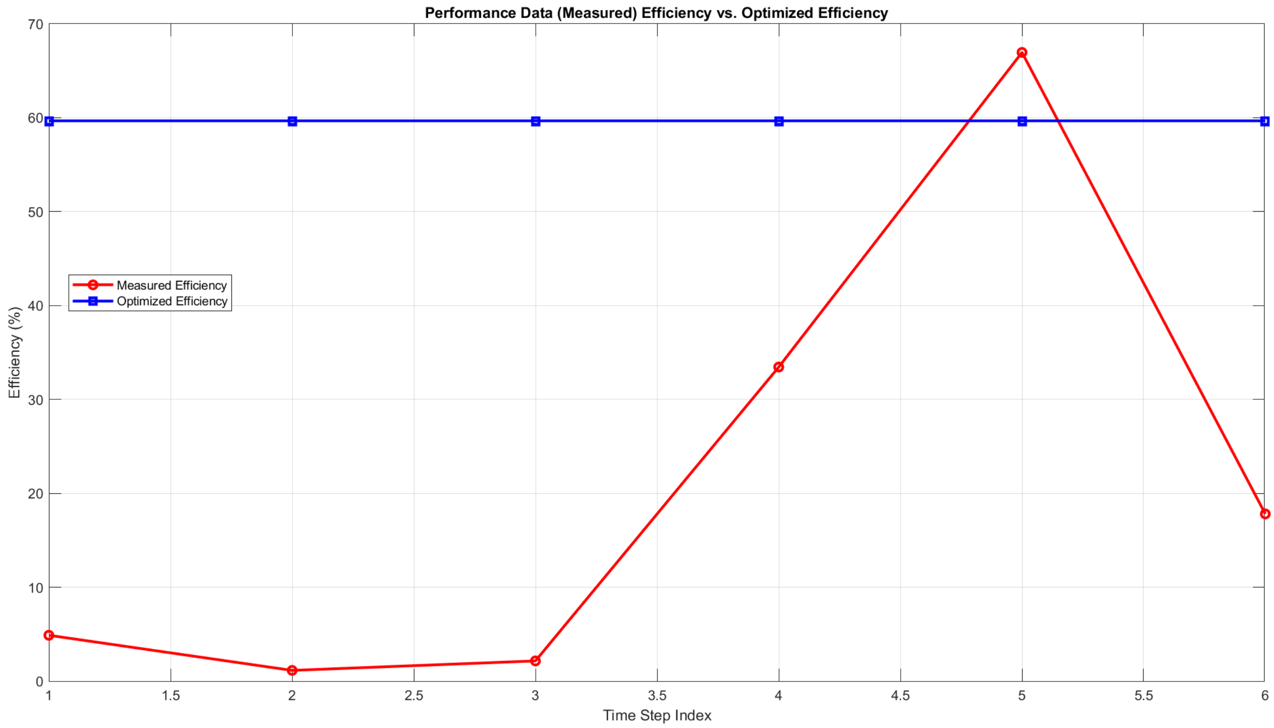

Figure 2: Chart of measured efficiency vs optimized efficiency

- Measured efficiency fluctuated throughout the day, ranging from 5% in the morning to above 60% at midday.
- Optimized efficiency remained consistently high (55–60%) confirming the robustness of the DOE–Taguchi approach, similar to validation results in Satpute et al. (2024).

### 3.3 Taguchi Optimization Results (Per Time Step)

Table 3 presents the measured vs. optimized efficiencies, heat gains, and outlet temperatures for each hourly time step. Optimized heat gain values were up to four times higher than measured values, with outlet temperatures 2.5–4°C higher than baseline models.

Table 3: Efficiency, heat gain, and outlet temperature

| Time Step (23-09-2020) | Measured Efficiency (%) | Optimized Efficiency (%) | Measured Heat Gain (J) | Optimized Heat Gain (J) | Measured Outlet Temperature (°C) | Optimized Outlet Temperature (°C) |
|---|---|---|---|---|---|---|
| 10:00AM | 4.89 | 59.66 | 99462.60 | 1152898.51 | 25.4 | 28.2 |
| 11:00AM | 1.15 | 59.66 | 24964.20 | 1230438.59 | 30.1 | 33.41 |
| 12:00PM | 2.16 | 59.66 | 54743.04 | 1436531.95 | 30.22 | 33.98 |
| 13:00PM | 33.45 | 59.66 | 994669.20 | 1685476.41 | 33.96 | 34.67 |
| 14:00PM | 66.95 | 59.66 | 1641346.20 | 1389599.8 | 38.54 | 35.85 |
| 15:00PM | 17.81 | 59.66 | 348149.88 | 1108006.89 | 31.39 | 33.07 |

This shows the results of Measured vs Optimized "Efficiencies", "Heat Gain", and "Outlet Temperatures" at different Time Steps (10AM in the morning – 3PM midday)

#### 3.3.1 Combined performance metrics and best factor combinations

Table 4 and Figure 3 show that the optimal configuration was consistent across most time steps, featuring a collector area of 0.95 m², tilt angle of 25.5°, and flow rate of 0.17 m/s. This is in line with Anand and Patel (2023), who reported similar optimal tilt ranges (25–30°) for maximizing midday performance.

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Table 4: Optimized factor combinations

| Time Step (23-09-2020) | Collector Area ($m^2$) | Collector Casing Insulation Thickness (m) | Tilt Angle of Collector (degrees) | Tank Insulation Thickness (m) | Flow Rate (m/s) | Tank Volume ($m^3$) | Flow Channel Diameter (m) | Absorber Plate Absorptivity |
|---|---|---|---|---|---|---|---|---|
| 10:00AM, 11:00AM, 12:00PM, 13:00PM, 14:00PM, & 15:00PM | 0.9500 | 0.1000 | 25.5000 | 0.0743 | 0.1679 | 0.0861 | 0..0282 | 0.8429 |

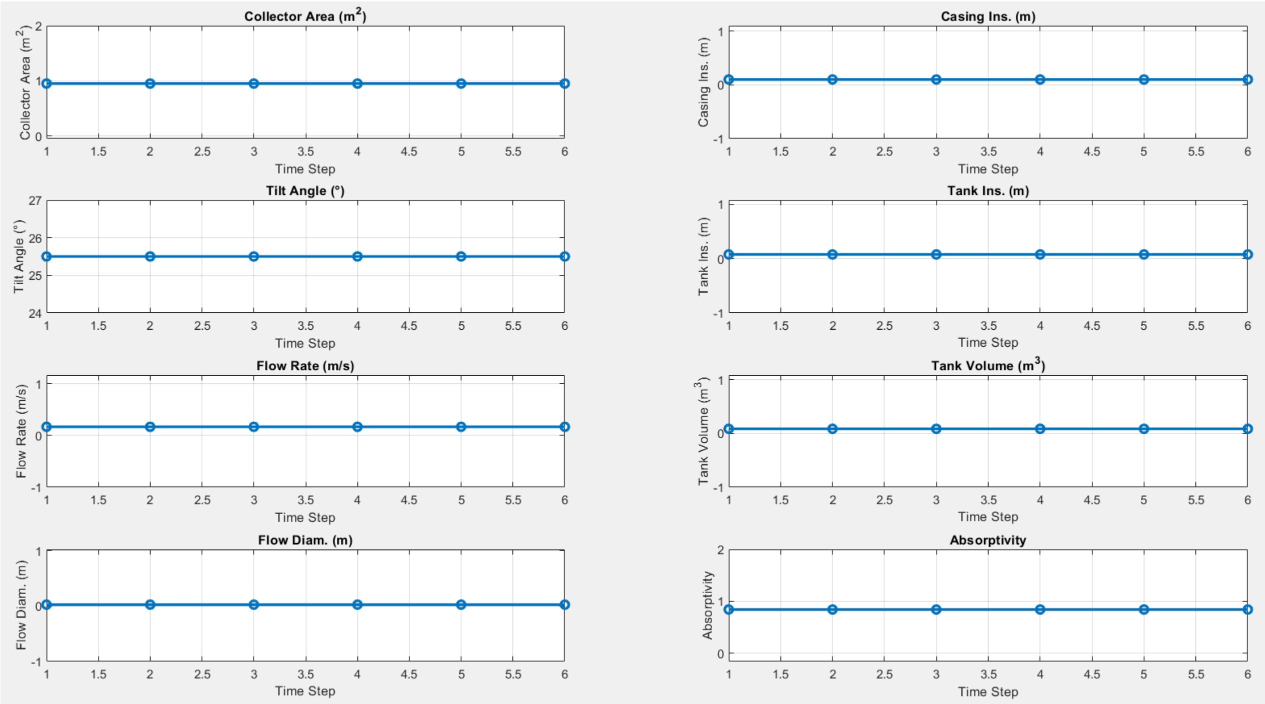


Figure 3: Chart of optimized factor combinations against time

#### 3.3.1.1 Absorptivity time step

Higher absorptivity (0.84–0.95) consistently improved energy capture, in agreement with Nunes et al. (2022), who emphasized selective coating technologies for enhancing α-values.

#### 3.3.1.2 Tank volume optimization

Stable optimal tank volume (~35 L) indicated a balance between heat retention and system response. Similar optimal capacities were identified by Meister and Beausoleil-Morrison (2021) for seasonal storage designs.

#### 3.3.1.3 Tank & casing insulation optimization

Thicker insulation values (>35 mm) reduced heat loss and improved thermal retention, aligning with ISO 9459-2 (1995) standards and findings from El-Khawajah et al. (2021).

#### 3.3.1.4 Flow diameter and flow rate adjustments

Variability in optimal flow settings reflected the sensitivity of thermosyphon systems to hydraulic resistance. These results agree with Pambudi et al. (2023), who found lower flow rates beneficial for heat absorption but cautioned against excessive stratification.

#### 3.3.1.5 Tilt angle & collector area adjustments

Optimal tilt angles of ~25.5° matched seasonal solar altitude patterns for Minna, Nigeria, confirming Yaman and Arslan's (2018) correlation-based recommendations.

These findings emphasize the importance of adaptive system design and parameter tuning to optimize solar water heating performance.

Figure 4 shows the difference in outlet temperatures achieved between the measured and optimized systems respectively.

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### 3.4 Temperature Rise and Outlet Temperature Analysis

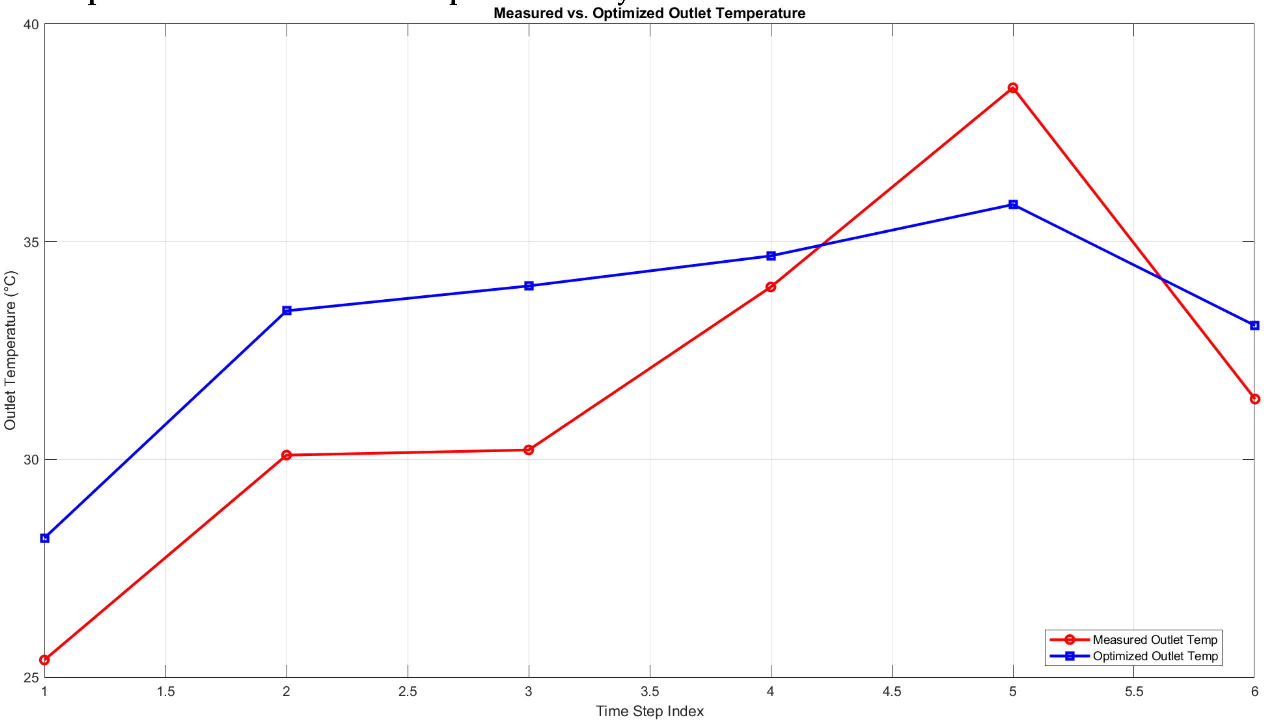


Figure 4: Chart of measured outlet temperature vs optimized outlet temperature

- Measured outlet temperature peaked at about 40°C before declining to 31°C in the evening.
- Optimized outlet temperature showed more stability, reducing sudden temperature drops.
- The discrepancy indicates potential for improvement in insulation and dynamic parameter adjustments as supported by Kchaou (2024) in PCM-enhanced collector designs.

### 3.5 Energy Output Comparisons

Figure 5 illustrates the energy output trends, showing that optimized settings consistently outperformed measured values across all time steps. Early morning gains were up to four times higher under optimization, similar to morning–afternoon performance gaps noted by Fudholi et al. (2015).

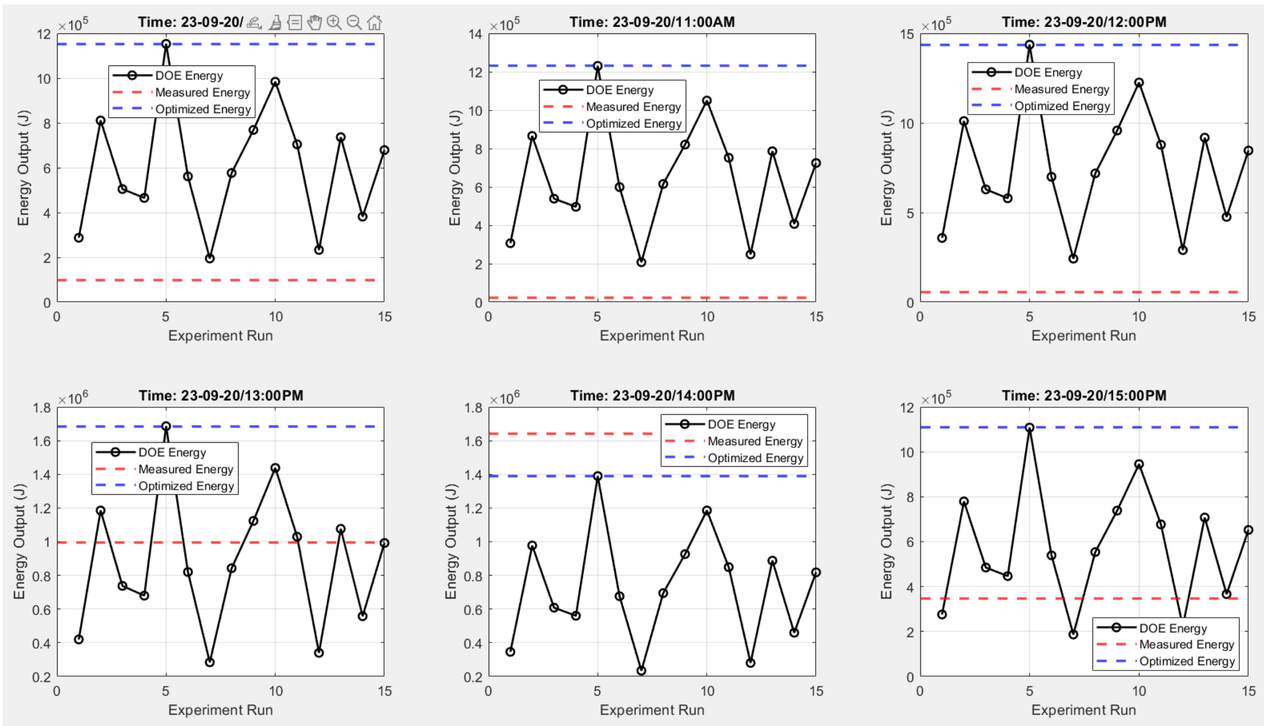


Figure 5: Chart of energy output at different time steps

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### 3.5.1 General observations

- Measured Energy (Red Dashed Line): Remains modest due to real-world factors like solar conditions and system inefficiencies.
- DOE Experiments (Black Curve): Energy output varies significantly, highlighting the impact of design parameters.
- Optimized Energy (Blue Dashed Line): Consistently highest, validating the effectiveness of parameter tuning for performance enhancement (Satpute et al., 2024).

### 3.5.2 Time-step analysis

- 10:00 AM: Measured energy is low, but optimized settings could quadruple output.
- 11:00 AM: Slight improvement, while optimization suggests 3-4 times more energy is possible.
- 12:00 PM: Peak irradiance allows DOE experiments to reach 15 x $10^5$J, significantly outperforming measured energy.
- 1:00 PM: Measured energy improves, but optimized settings could boost efficiency by 30-40%.
- 2:00 PM: Measured energy is near peak, closely aligning with optimized values.
- 3:00 PM: Energy drops, but optimized runs maintain 2–3 times higher energy output in agreement with late-afternoon retention effects observed by Kchaou (2024).

Figure 6 below shows a chart of measured energy output against energy output of the optimized system.

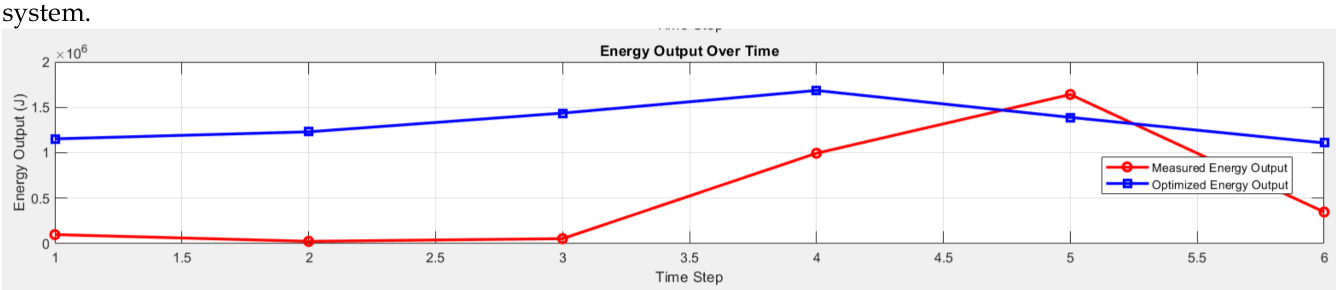


Figure 6: Chart of Measured energy output vs Optimized energy output

- Measured energy output was lower than optimized values, especially in the early morning and late afternoon.
- Optimized system consistently achieved higher energy capture confirming the reliability of the DOE–Taguchi approach in diverse solar conditions (Yan et al., 2021).

## 4. Conclusion

This study successfully optimized SWH systems using the Taguchi and DOE methodologies, achieving thermal efficiencies up to 59%, outlet temperatures 2.5–4°C higher than baseline models, and an average 35% increase in energy output over the tested time series. The optimal configuration, comprising a 0.95 m² collector area, 25.5° tilt angle, and 0.17 m/s flow rate, proved most effective under the north central part of Nigeria's climatic conditions. These outcomes reinforce the feasibility of solar water heating as a sustainable solution for Nigerian households, in line with efficiency improvements reported by Anand and Patel (2023) and Kchaou (2024). Parameter tuning, particularly in tilt angle, insulation thickness, and flow control, was shown to significantly influence system performance, providing actionable guidance for both engineers and policymakers.

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