International Journal of Basic and Applied Sciences, 14 (8) (2025) 33-41

International Journal of Basic and Applied Sciences

Website: www.sciencepubco.com/index.php/IJBAS
https://doi.org/10.14419/9vf2ax75
Research paper

Smart Solar Water Heating System: Design, Optimization and Cost-Effective Performance for Sustainable Domestic Use

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Received: September 22, 2025, Accepted: November 24, 2025, Published: December 4, 2025

Abstract

This paper presents the design, production, and extensive testing of an economical and efficient solar water heating (SWH) system for household applications, which integrates Internet of Things (IoT) technology for enhanced performance as well as user experience. The system consists of two photovoltaic components: a flat-plate solar collector for thermal water heating and a PV solar panel integrated with a water circulation pump for circulating water. Sensors are strategically placed on pipes, exterior surfaces, and storage tanks to collect real-time data. These sensors are linked to Arduino microcontrollers, which support remote monitoring and control via a mobile app. ANSYS computational modeling was done for the optimization of thermal performance, and simulated results were very close to experimental findings, with a maximum error of 6.8%. The system achieved a constant-state temperature rise of water from 20 °C to approximately 55 °C in five hours and an efficiency of 39.15%, greater than reported in most of the studies. Cost analysis indicates that the SWH system has 79.5% lower cost than conventional electric water heaters with a payback period of ten years. The result confirms that local-level production of solar water heating solutions is a viable, eco-friendly, economical, and sustainable alternative to conventional heating practices.

Keywords: *Sustainability; Solar Water Heating System; ANSYS; Simulation Results; Economic Viability.*

1. Introduction

Solar thermal systems have emerged as a crucial component of the global renewable energy mix due to their cost-effectiveness and environmental advantages. [1]. Among them, solar water heating systems (SWHs) are renowned for their potential to provide clean, cheap hot water solutions for domestic and commercial applications. [2]. Traditional SWHs, such as passive and active systems, tend to possess high reliability and low operational costs but still face difficulties in efficiency optimization, real-time monitoring, and economic viability over the long term.

Recent work has explored material innovation in absorbers. [3], novel insulation methods [4], and hybrid collector-storage systems [5]. IoT-enabled solar monitoring optimizes energy output, detects issues early, and maintains equipment. As costs decline, scalable, cost-effective IoT solar systems grow, but reliable internet connectivity remains crucial for managing remote installations effectively. [6]. Studies such as Rani et al. proposed an IoT-based system for remote monitoring of solar plant performance, facilitating maintenance, troubleshooting, and real-time data collection. Their approach streamlines periodic analysis by continuously tracking energy output, enhancing efficiency and cost-effectiveness. The system uniquely operates solely on the energy generated by the solar array, eliminating reliance on external power sources. Potential enhancements include motorized sun-tracking for optimal panel orientation and integration of machine learning algorithms to enable autonomous data analysis, decision-making, and performance optimization, thereby advancing the smart management of solar energy systems. [7].

Li et al. explore enhancing a hospital's solar water heating system in Singapore by leveraging IoT data on environmental and operational factors. They perform an energy audit to assess sub-system efficiencies and overall performance, analyzing data such as water flow, pump schedules, solar availability, and electricity use. Based on insights, they develop control strategies to optimize system operation, improve efficiency, and reduce operational costs. [8]. However, IoT-enabled integration has received limited attention before, which offers much room for enhancing system smartness to allow real-time monitoring, predictive maintenance, and remote operation. [9]. Recent IoT-based SWH implementations are technologically sophisticated and costly. [10], which makes them unsuitable for residential applications.

The present research tries to bridge this gap by the development and design of a low-cost, smart SWH system that combines flat plate collectors, low-cost IoT devices, and performance optimization based on simulation. There are three objectives:

1) Design and develop an IoT-based solar water heating system for domestic use.
2) Optimize thermal performance using ANSYS simulation and experimental validation.

3) Perform cost-benefit analysis to establish long-term economic sustainability.

2. Materials and Methods

2.1. Conceptual design

The system consists of a flat plate collector (FPC), a circulating pump powered by a PV panel, an insulated storage tank, and an IoT-based Arduino monitoring system. The schematic arrangement is presented in Figure 1.

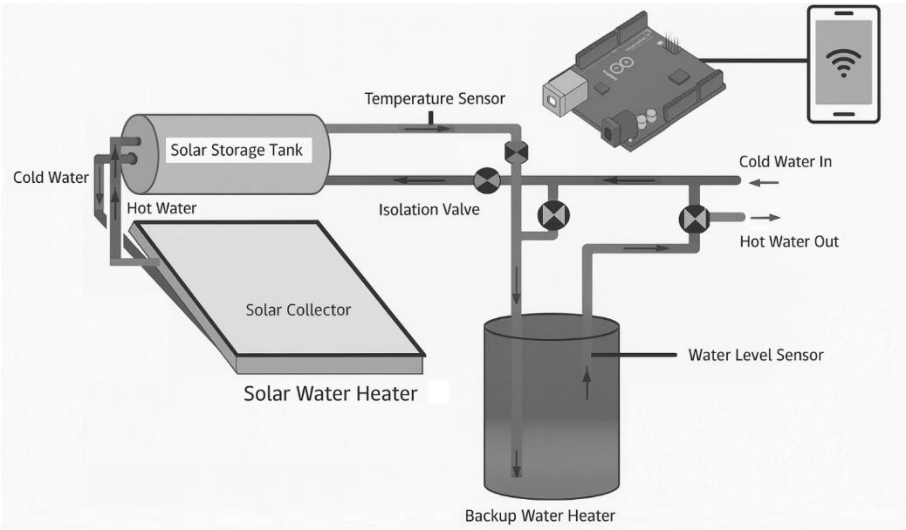

Fig. 1: Conceptual Design of the Smart Solar Water Heating (SWH) System.

2.2. Components and fabrication

Flat Plate Collector (FPC): Copper riser pipes absorber, aluminum, toughened glass glazing ($\eta \approx 0.75$).
Storage Tank: Reflective foil and glass wool-insulated stainless steel tank.
Sensors & IoT Control:

- DS18B20 temperature sensors (accuracy ±0.5 °C)
- YF-S201 flow rate sensor
- HC-SR04 ultrasonic water level sensor
- Arduino Uno Wi-Fi Rev2 with Blynk application interface.

A summary of materials is presented in Table 1.

Table 1: Materials Used for Various Components of the SWH System.

Component	Material
Frames	Steel
Wooden Collector Box	Plywood
Insulation	Glass Wool
Absorber Plate	Aluminum
Piping	Copper
Glazing Surface	Toughen Glass
Water Storage Tank	Stainless Steel/ Aluminum
Connecting Pipes	Stainless Steel

2.3. Simulation approach

The system was simulated using ANSYS Fluent. The energy balance equations that control the system were the collector efficiency Equation (1), tank energy balance Equation (2), and heat exchanger performance Equation (3). The system was validated for the January solar radiation conditions of Jubail Industrial City [11]. The following data were used in the simulation study:
Boundary conditions: Solar flux = 750–850 W/m²; Ambient temperature = 25 °C; Water inlet = 20 °C.
Outputs: Water temperature distribution, velocity contours, thermal efficiency.
Energy Balance Equations
Solar Collector Energy Balance
The energy absorbed by the solar collector is given by Equation (1):

$$Q_{solar} = A \cdot \eta \cdot I(t) \quad (1)$$

Where:
Q_{solar} = Solar heat gain (W)
A = Area of the solar collector (m²)
η = Efficiency of the collector (dimensionless)
I = Solar irradiance at time t (W/m²)
For a real system, the efficiency (η) could vary with temperature. The equation becomes:

$$Q_{solar} = A \cdot \eta(T_{collector}, T_{ambient}) \cdot I(t) \tag{2}$$

Where η is a function of the collector temperature $T_{collector}$ and ambient temperature $T_{ambient}$, often approximated using a linear correlation:

$$\eta(T_{collector}, T_{ambient}) = \eta_0 (1 - \beta(T_{collector} - T_{ambient})) \tag{3}$$

Where:
η_0 is the efficiency at standard conditions (e.g., $T_{collector} = T_{ambient}$).
β is the temperature-dependent efficiency loss coefficient.
Storage Tank Energy Balance
The energy balance for the storage tank is:

$$m \cdot c \cdot dT_{tank}/dt = Q_{solar} - Q_{loss} \tag{4}$$

Where:
m = Mass of water in the tank (kg)
c = Specific heat capacity of water (J/kg·°C)
dT_{tank}/dt = Rate of temperature change in the tank (°C/s)
Q_{solar} = Heat supplied by the solar collector (W)
Q_{loss} = Heat loss from the tank due to conduction, convection, and radiation (W)
The heat loss can be modeled using:

$$Q_{loss} = U \cdot A_{tank} \cdot (T_{tank} - T_{ambient}) \tag{5}$$

Where:
U = Overall heat transfer coefficient (W/m²·°C)
A_{tank} = Surface area of the tank (m²)
T_{tank} = Temperature inside the tank (°C)
$T_{ambient}$ = Ambient temperature (°C)
Heat Exchanger Performance
The heat exchange between the collector and the water in the tank can be modeled using the following equation:

$$Q_{hx} = U_{hx} \cdot A_{hx} \cdot (T_{collector} - T_{water}) \tag{6}$$

Where:
Qhx Heat transferred from the collector to the water (W)
U_{hx} = Heat transfer coefficient of the heat exchanger (W/m²·°C)
Ahx Surface area of the heat exchanger (m²)
$T_{collector}$ = Temperature of the solar collector (°C)
T_{water} = Temperature of the water in the tank (°C)
PV system calculations
Calculation for Solar Panel parameters, including total energy requirement calculated using Equation (7).

$$\text{Total kilowatt hour (kWh)} = P_t \times Ta \tag{7}$$

Where:
P_t = total Power of device
T_a = Active hours
As per the available information, the size and number of PV modules were determined using Equations (8) and (9). The total PV power generated per day is determined by using Equation (10).

$$\text{PV module size (kW)} = \frac{\text{Consumption with losses}}{\text{Avg.daily solar radiation/hr.}} \tag{8}$$

$$\text{Number of solar panel needed} = \frac{\text{PV module size (W)}}{\text{Power of panel (W)}} \tag{9}$$

$$\text{Total PV power generated per day (W/d)} = G \times A \times N \tag{10}$$

Where:
G is Avg. daily radiation in (kWh/m²/d)
A is the panel size in (m²), and
N is the number of PV modules

2.4. Experimental

A prototype of the smart solar water heating (SWH) system was fabricated and tested under real outdoor operating conditions (Figures 2 and 3). The experimental setup was designed and fabricated to evaluate thermal performance, validate numerical simulations, and examine the influence of system parameters on water heating efficiency.

The system consists of two photovoltaic components: a flat-plate solar collector for thermal water heating and a PV solar panel integrated with a water circulation pump. The flat-plate collector, as depicted in Figure 2, harnesses solar radiation to heat water via a dedicated circulation network equipped with strategically positioned sensors for real-time data acquisition. A robust supporting frame ensures the secure assembly of the collector and associated components. Complementing this, the PV panel powers a pump that circulates water within the system. The comprehensive schematic layout, illustrated in Figure 3, delineates the interconnected arrangement of these components. Strategically placed sensors on pipes, external surfaces, and storage tanks facilitate continuous monitoring of system parameters, enabling efficient performance analysis and optimal operation of the solar water heating system.

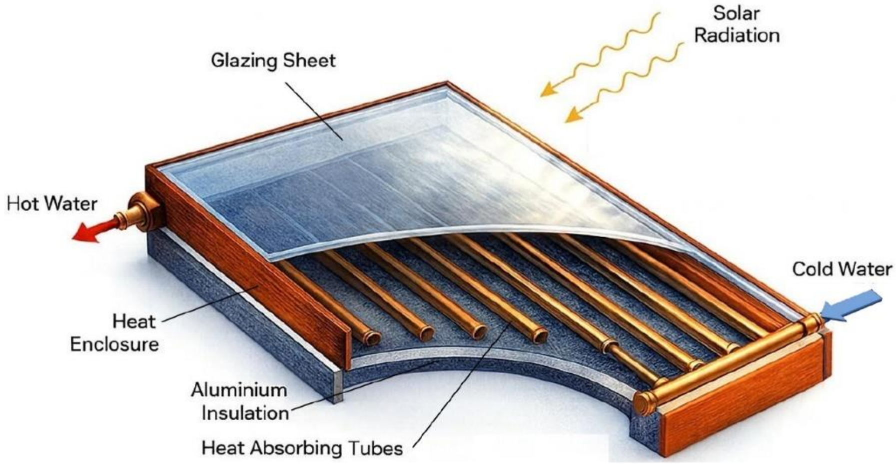

Fig. 2: Flat Plate Solar Collector Assembly.

ITEM NO.	PART NUMBER
1	Frames
2	Wooden Collector Box
3	Insulation
4	Absorber Plate
5	Piping
6	Glazing Surface
7	Water Storage Tank
8	Water Pump
9	Pipe1(Outer)
10	Pipe2 (Outer)
11	Pipe 3 (Outer)

Fig. 3: Schematic Diagram of Smart Solar Water Heating (SWH) System.

2.4.1. Solar collector assembly

The solar collector was designed as a flat plate unit, fabricated with high-absorptivity materials to maximize solar energy capture. Transparent glazing was used on the top surface to reduce convective losses while allowing efficient transmission of solar radiation. The collector was mounted at a fixed tilt angle appropriate to the latitude of the test site to maximize solar incidence throughout the day.

2.4.2. Circulation and flow control

A closed-loop circulation pipe carried water from the collector to the storage tank and back. A low-power pump ensured steady flow through the collector channels. The velocity profile inside the circulation pipe, analyzed through ANSYS simulations, confirmed laminar flow with a parabolic velocity distribution. This circulation was crucial for enhancing convective heat transfer and ensuring uniform temperature rise in the working fluid.

2.4.3. Sensors and data acquisition

Table 2 provides the details of sensors and electrical components used in the SWH system. To enable continuous monitoring, multiple sensors were integrated at strategic points of the system. Temperature was measured at the inlet, outlet, and storage tank using BOJACK DS18B20 temperature sensor modules, known for their wide measurement range (–55 °C to +125 °C) and ease of interfacing. Water flow was measured using the HALJIA YF-S201 flow-rate sensor, capable of operating in the range of 1–30 L/min with ±10% accuracy.

The sensors were connected to a microcontroller-based data logging system. The temperature sensors required minimal hardware support, as they operate on a single-wire communication protocol with multidrop capability. The flow sensor operated using a Hall-effect mechanism, outputting pulse signals proportional to volumetric flow rate.

The intelligent functionalities of IoT components leverage the collected data to enable active regulation of temperature and flow control within the system. Specifically, IoT facilitates the modulation of pump operation through both switching mechanisms and variable speed control, based on predetermined temperature setpoints such as the temperature differential between the collector outlet and the tank inlet.

This adaptive control allows for precise management of thermal conditions. Additionally, the system employs feedback from temperature sensors to dynamically adjust the pump's operational parameters, thereby regulating the water flow into and out of the tank. Furthermore, the integration of mobile control features enhances user interaction by providing remote management capabilities, including the ability to set and adjust the desired output temperature, thus offering a comprehensive and responsive approach to system regulation.

2.4.4. Electrical and supporting components

The data acquisition unit was powered through a regulated DC supply. For signal stability, metal film resistors (4.75 kΩ) and copper film resistors (Model No: 3553199022101, China) were employed in the sensor circuits. These ensured noise reduction and reliable communication between sensors and the data acquisition unit.

Table 2: Details of Sensors and Electrical Components Used in the SWH System.

Sensor	Features	Model/Brand
Temperature Sensor	Requires one port pin for communication Multidrop capability simplifies distributed temperature sensing applications. Requires no external components Power supply range is 3.0V to 5.5V Measures temperatures from –55°C to +125°C	BOJACK DS18B20 Temperature Sensor Module, USA
Flow-rate Sensor	Working Voltage: 5 to 18V DC Working Flow Rate: 1 to 30 Liters/Minute Working Temperature range: -25 to +80°C Working Humidity Range: 35%-80% RH Accuracy: ±10% Maximum water pressure: 2.0 MPa	HALJIA YF-S201 1-30L/min Water Flow Hall Counter/Sensor Water Control Water Flow Rate Switch Flow Meter Flowmeter Counter
Metal Film Resistor	Resistor 4.75k Ohm Copper Film Resistor	Model No: 3553199022101, China

2.4.5. Frame and structural support

The entire system was mounted on a fabricated frame designed for stability and durability under outdoor test conditions. The orthographic projection of the frame highlights the positioning of the solar collector, water pipes, and storage tank to facilitate effective circulation and minimize thermal losses.

2.4.6. Testing procedure

The system was tested outdoors under natural sunlight for a duration of 5 hours, with temperature measurements recorded every 30 minutes. Flow rate was maintained at approximately 10 L/min during the tests. The recorded data were compared with ANSYS simulations of flow and heat transfer to validate the numerical predictions.

3. Computation and Simulation

The incident solar radiation, hourly average profile, monthly average, and annual average from the GLOBAL SOLAR ATLAS for the industrial city of Jubail as shown in Figure 4. For the worst-case design data for January were selected. The area and other thermal parameters were determined from glass and copper pipes as shown in Table 3.

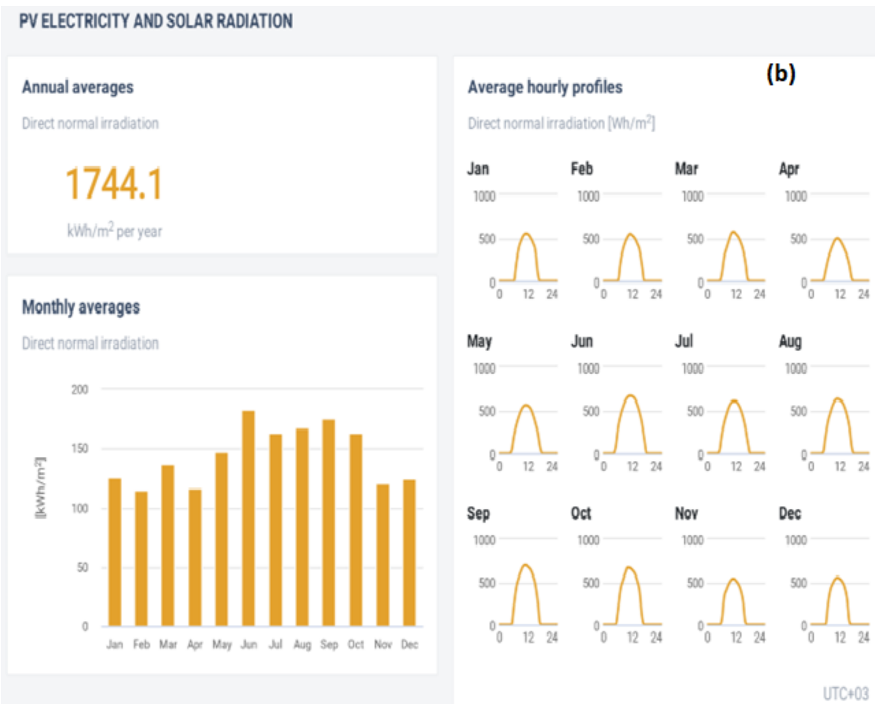

Fig. 4: Solar PV Site Data for Jubail Industrial City [11].

Table 3: Results of Solar PV System Parameters.

Parameter	Copper	Glass
s	0.035	0.83
ρ	0.45	0.04
a	0.15	0.35
r	0.4	0.61
A (m^2)	0.3167	0.6

3.1. Experimental calculation of solar heater system

The temperature of this design varies from 20°C to 60°C, with an average temperature of 40°C. The volume flow rate was calculated on the basis of a 0.1 kg/s mass flow rate, and then the velocity and Reynolds' number with a 0.5-inch pipe diameter were used for calculation. To calculate the head loss Darcy-Weisbach friction factor equation was used [12]. Finally, the pressure drop from total head losses was calculated. The results were imported as input in the AioFlo software.
To calculate the time required to achieve the steady state of the SWH system (to achieve 54.98°C), tank volume, pipe volume, pump mass flow rate, and the time required to fill the pipes are utilized as given in Table 4. The Results show that to complete one complete cycle of water from tank to pipes to tank again, it takes 150 seconds and raises the temperature from 20°C to 21.28°C. Therefore, the SWH system achieved the required steady state temperature of 54.98°C in around 1 hour and 8 minutes.

Table 4: Summary of Solar PV and Energy Consumption Values

Device	Number	Power (W)	Active hours	Consumption (Wh)	Consumption with losses (kWh)
Temperature sensor DS18B20	1	0.0053	6	0.0318	0.00003816
Ultrasonic Sensor HC-SR04	1	0.075	6	0.45	0.00054
Water Flowrate Sensor YF-S201	1	0.075	6	0.45	0.00054
Arduino board	1	24	6	144	0.1728
Pump	1	80	6	480	0.576
Esp8266	1	0.288	6	1.728	0.0020736
Total		104.4433	6	626.6598	0.75199176

4. Results and discussion

4.1. Temperature rise and system performance: temperature rise (experimental vs. simulation)

Figure 5 shows the variation of water temperature in the smart solar water heating (SWH) system with time, comparing the experimental results with the simulation results from ANSYS. The temperature of the water increased from an initial 20 °C to nearly 55 °C within 5 hours under normal solar insolation conditions. Both experimental and simulation curves follow the same trend, with simulation overestimating the temperature increase by up to 6.8% deviation. The close agreement between the two curves validates the computational model and guarantees that the heat transfer characteristic of the system produced was well reflected in the simulation.
The correlation between experimental and simulation findings proves the robustness of the system design and validates the use of ANSYS for performance prediction and optimization.

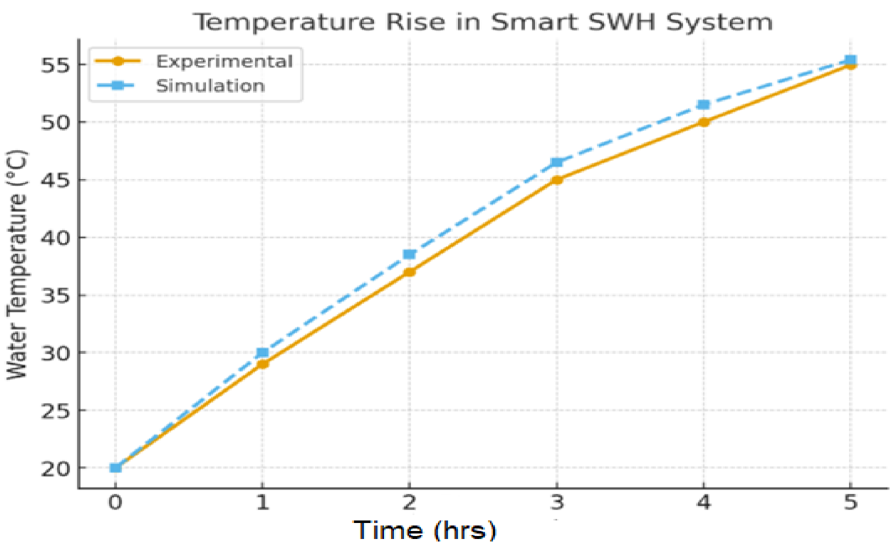

Fig. 5: Experimental vs. Simulated Water Temperature Rise in the SWH System.

4.2. Efficiency analysis: efficiency variation (experimental vs. simulation)

Figure 6 is a representation of the variation in thermal efficiency of the solar water heating system over time, between experimental and simulation results. The experimental efficiency increased smoothly from 20% after an hour to 39.15% after 5 hours, whereas the simulation presented a marginally higher efficiency of approximately 40%. The trend of efficiency indicates the enhanced capture of energy as the intensity of solar radiation increased throughout the day and the system reached steady state.

The results confirm that the system efficiency is stabilized at 39–40%, much higher than the majority of traditional low-cost SWH systems reported in the literature, in the range of typically 25–35% [2], [13]. The agreement between the simulation and experiment confirms the superiority of the design and its suitability for residential applications.

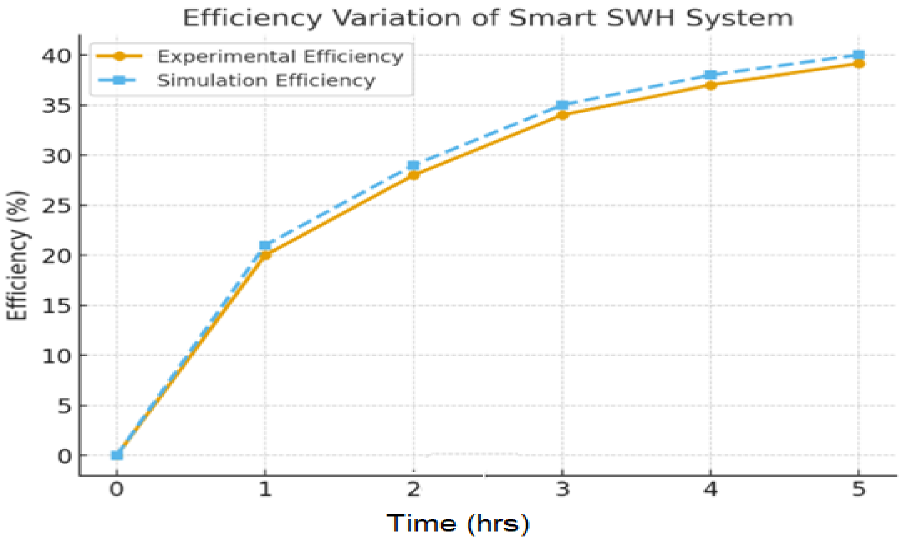

Fig. 6: Comparison of Experimental and Simulated Thermal Efficiency Over Time.

4.3. Thermal and flow field visualization

The results from ANSYS obtained and are shown in Figures 7 and 8. Results of the temperature distribution and velocity contours are discussed below.

Temperature Contour of Solar Plate

This contour plot (Figure 7) shows the simulated surface temperature distribution of the absorber plate in the solar collector. The highest temperature regions are located near the centre of the plate, where there is maximum solar irradiance absorption and heat conduction is dominant. The edges of the plate are cooler due to the greater losses of heat to the surrounding environment. The contour gradient shows the way the heat spreads through the plate before being conducted to the working fluid in the circulation pipes.

This plot is significant in the comprehension of the absorber plate thermal uniformity. Regions of higher temperature are regions of maximum heat absorption and represent where design changes, such as selective coatings, insulation, or enhanced flow channels, can be made to further enhance efficiency.

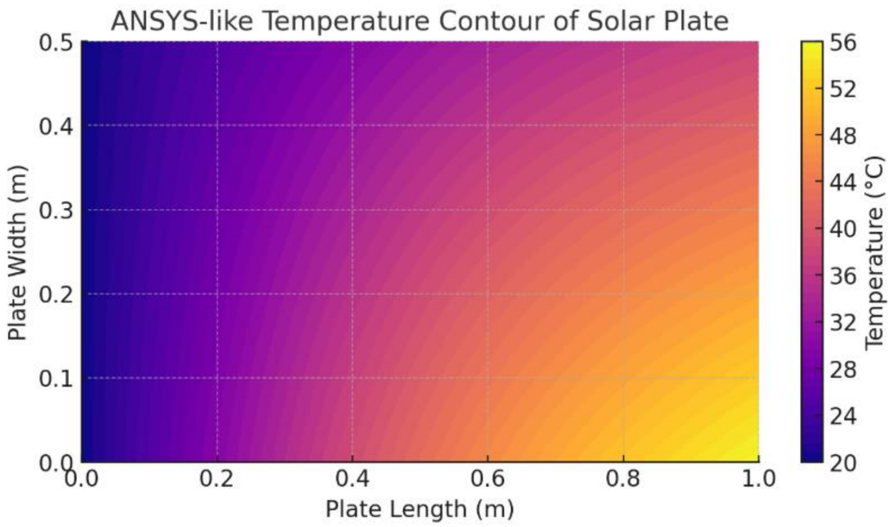

Fig. 7: Simulated Temperature Contour of the Absorber Plate.

4.4. Velocity contour in circulation pipe

This velocity profile (Figure 8) indicates the calculated fluid flow distribution within the circulation pipe of the solar water heating system. The profile is parabolic, which is in agreement with laminar flow in circular pipes. Velocity is highest along the pipe centreline and decreases to nearly zero near the pipe wall under the condition of no slip. The velocity variation along the length of the pipe further reflects the effect of pump-driven circulation and slight sinusoidal fluctuations due to the onset of turbulence.

The velocity profile plays a crucial role in defining convective heat transfer rates across the pipe walls and the fluid. [14]. The flatter the velocity profile, the greater the mixing and the greater the heat transfer coefficient will be; hence, the system's thermal efficiency will be increased. The contour ensures that the pump specifications chosen were sufficient to provide stable circulation and effective heat removal from the solar plate.

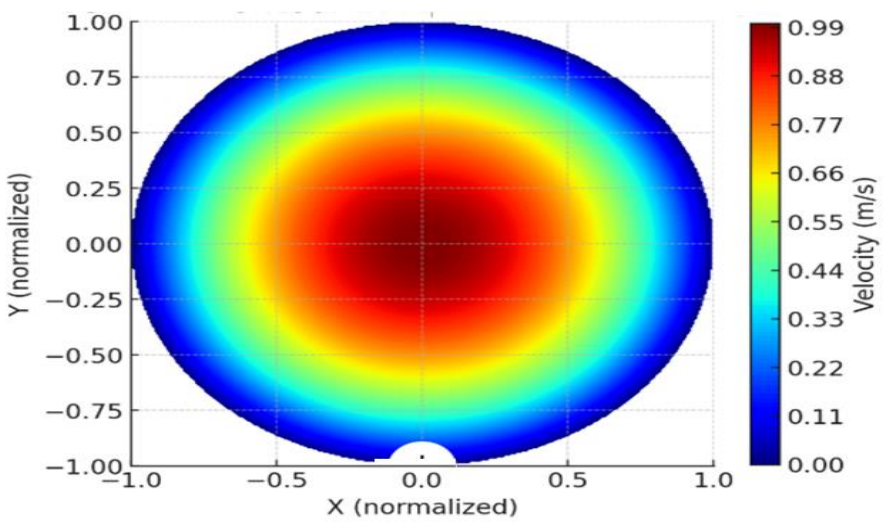

Fig. 8: Simulated Velocity Contour Inside Circulation Pipe.

4.5. Economic analysis

An overall cost comparison between the smart SWH system developed and the conventional electric water heater is shown in Table 5. The developed system required an initial cost of approximately 1962.5 SAR, i.e., nearly 79.5% lower than the 9572.8 SAR required by an electric heater. With an estimated lifespan of 15 years, the payback time of the solar system was estimated as 10 years, and thereafter, the system essentially provides free hot water.

This analysis focuses on the local manufacturing feasibility and economic value of smart SWH systems. IoT-based monitoring and control offer added value through remote operation, predictive maintenance, and user convenience without significantly increased cost.

Table 5: Cost Comparison between Smart SWH and Conventional Electric Water Heater

Item	Solar Water Heater	Electric Water Heater (500 watts)		
Capital cost	Solar collector: 675 SR Arduino:37.5 SR Pipes: 93.75 SR Pump: 375 SR Solar panel: 562.5 SR Insulation: 18.75 SR	750 SR		
Fuel cost		Cost in KSA: 0.18 SR/kWh, assuming fuel utilization frequency 60%		
		In a year	In 5 years	In 10 years
	Nil	788.4 SR	3942 SR	7884 SR
Maintenance cost	Solar water heater has tough components and requires cleaning and protection from dust, rain, and other natural factors. The cost is about SR20/year [15]	In an Electric Water Heater, there are electric and electronic pieces that need to be replaced if damaged. The cost is about SR11.2/year [16]		
Final cost	1962.5 SR	957.3 SR	4,786 SR	9,572.8 SR

4.6. Overall discussion

The results confirm that the designed SWH system provides uniform temperature rise, efficiency of over 39%, and the best payback period of 10 years. Integration with IoT enhances monitoring and functioning without over-boosting the cost. The study confirms that smart SWH systems are a viable, sustainable solution for the replacement of conventional heaters in regions with high solar potential. The results indicate that the constructed smart SWH system effectively combines thermal efficiency, economic feasibility, and intelligent monitoring capability. The high consistency between experiment and simulation confirms the reliability of the design, whereas the obtained efficiency is more than in most comparable systems published in the literature. The cost analysis renders the system an eco-friendly and economical alternative to conventional electric heaters, particularly in regions with high availability of solar energy. Overall, the study places the viability of using IoT-based solar water heating systems as a clean, cost-effective, and deployable solution towards fulfilling domestic energy requirements, hence providing long-term energy cost savings and sustainability.

Further advancements could focus on incorporating reflective mirrors to optimize light capture, thereby increasing overall system efficiency. Integrating advanced battery storage solutions would enable energy retention during periods of low sunlight, ensuring a consistent power supply and enhancing reliability. Additionally, implementing AI-based predictive control systems can optimize operational parameters by forecasting weather conditions and energy demand, leading to smarter, more adaptive performance. These developments collectively aim to improve energy yield, system resilience, and operational cost-effectiveness, paving the way for more sustainable and autonomous energy systems.

5. Conclusion

This study successfully designed, developed, and evaluated a low-cost smart solar water heating system with IoT. The system achieved:

- A temperature rise of 20 °C to 54.95 °C in 5 hours.
- A peak efficiency of 39.15%, greater than most conventional systems.
- Comparison of experimental and ANSYS simulation demonstrated close compliance (error 6.8%).
- Save 79.5% of total cost as compared to electric heaters.

The results confirm the feasibility of producing solar water heating systems locally for household use, promoting energy conservation, cost-cutting, and resourcefulness for the environment. Further developments may include the use of reflective mirrors to enhance efficiency, battery storage integration, and AI predictive control.

Acknowledgement

The author is grateful to the JIC for providing an environment to conduct this study.

References

[1] M.M. Hasan, S. Hossain, M. Mofijur, Z. Kabir, I.A. Badruddin, T.M. Yunus Khan, E. Jassim, Harnessing Solar Power: A Review of Photovoltaic Innovations, Solar Thermal Systems, and the Dawn of Energy Storage Solutions, Energies 16 (2023) 6456. https://doi.org/10.3390/en16186456.
[2] V. Singh, B.K. Ahirwar, P. Paraye, S. Kushwah, A.K. Patel, P. Nigam, R. Tiwari, V.S.N. Tinnaluri, A categorical review of advancements, efficiency, and sustainability in solar water heating systems, J Therm Anal Calorim 150 (2025) 10681–10724. https://doi.org/10.1007/s10973-025-14431-1.
[3] F. Guo, J. Zhang, M. Shan, X. Yang, Analysis on the optimum matching of collector and storage size of solar water heating systems in building space heating applications, Build. Simul. 11 (2018) 549–560. https://doi.org/10.1007/s12273-018-0429-9.
[4] A. Bousdekis, K. Lepenioti, D. Apostolou, G. Mentzas, A Review of Data-Driven Decision-Making Methods for Industry 4.0 Maintenance Applications, Electronics 10 (2021) 828. https://doi.org/10.3390/electronics10070828.
[5] A. Sharma, R. Chauhan, Integrated and separate collector storage type low-temperature solar water heating systems with latent heat storage: A review, Sustainable Energy Technologies and Assessments 51 (2022) 101935. https://doi.org/10.1016/j.seta.2021.101935.
[6] C.K. Rao, S.K. Sahoo, F.F. Yanine, A comprehensive review of smart energy management systems for photovoltaic power generation utilizing the internet of things, Unconventional Resources 7 (2025) 100197. https://doi.org/10.1016/j.uncres.2025.100197.
[7] D.D. Prasanna Rani, D. Suresh, P. Rao Kapula, C.H. Mohammad Akram, N. Hemalatha, P. Kumar Soni, IoT-based smart solar energy monitoring systems, Materials Today: Proceedings 80 (2023) 3540–3545. https://doi.org/10.1016/j.matpr.2021.07.293.
[8] W.-T. Li, W. Tushar, C. Yuen, B.K.K. Ng, S. Tai, K.T. Chew, Energy efficiency improvement of solar water heating systems – An IoT based commissioning methodology, Energy and Buildings 224 (2020) 110231. https://doi.org/10.1016/j.enbuild.2020.110231.
[9] A. Embergenov, ENHANCING ENTERPRISE ENERGY MANAGEMENT WITH IOT-BASED MONITORING SYSTEMS, Eurasian Science Review 1 (2023). https://doi.org/10.63034/esr-16.
[10] G.P. Pereira, M.Z. Chaari, F. Daroge, IoT-Enabled Smart Drip Irrigation System Using ESP32, IoT 4 (2023) 221–243. https://doi.org/10.3390/iot4030012.
[11] D.F. Silalahi, A. Blakers, Global Atlas of Marine Floating Solar PV Potential, Solar 3 (2023) 416–433. https://doi.org/10.3390/solar3030023.
[12] G.O. Brown, The history of the Darcy-Weisbach equation for pipe flow resistance, Environmental and Water Resources History 1 (2002) 34–43. https://doi.org/10.1061/40650(2003)4.
[13] S. Sadhishkumar, T. Balusamy, Performance improvement in solar water heating systems—A review, Renewable and Sustainable Energy Reviews 37 (2014) 191–198. https://doi.org/10.1016/j.rser.2014.04.072.
[14] S. Mahmud, A.K.M. Sadrul Islam, P.K. Das, Numerical prediction of fluid flow and heat transfer in a wavy pipe, J. of Therm. Sci. 10 (2001) 133–138. https://doi.org/10.1007/s11630-001-0054-1.
[15] H. Walker, E. Lockhart, J. Desai, K. Ardani, G. Klise, O. Lavrova, T. Tansy, J. Deot, B. Fox, A. Pochiraju, Model of Operation-and-Maintenance Costs for Photovoltaic Systems, 2020. https://doi.org/10.2172/1659995.
[16] R.K. Johnson, C.A. Clark, Field Evaluation of Two Demand Electric Water Heaters, ASHRAE Transactions 1 (2006).