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DEVELOPMENT OF AN ENERGY-EFFICIENT SOLAR WATER HEATER FOR RESIDENTIAL USE

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Abstract:

The development of energy-efficient solar water heaters is crucial for reducing residential energy consumption and promoting sustainable living. This paper presents the design, optimization, and evaluation of a solar water heater tailored for residential applications, with a focus on maximizing thermal efficiency while minimizing operational costs. Key aspects discussed include the selection of advanced materials for improved heat absorption, the integration of high-performance insulation to reduce thermal losses, and the implementation of user-friendly control systems for optimal operation. The study also examines the impact of geographic and climatic factors on system performance and explores strategies to enhance year-round reliability. Potential benefits such as reduced carbon footprint, lower utility bills, and increased adoption of renewable energy technologies in households are highlighted. The findings underscore the significance of continued innovation in solar water heating technology to meet the growing demand for sustainable and cost-effective residential energy solutions.

***IndexTerms* - Solar Water Heater, Renewable Energy, Coiled Steel Collector, Domestic Water Heating, Energy Efficiency, Sustainable Technology, Thermal Storage, Experimental Validation**

I. Introduction

Conventional electric water heaters typically consume about 2000 Watts of power, leading to high electricity costs and energy inefficiency in the long run. With growing concerns about energy consumption and environmental sustainability, there is an increasing demand for cleaner and more cost-effective alternatives. One such solution is the use of solar water heaters, which harness the abundant and renewable energy from the sun to heat water, offering a significant reduction in electricity usage—particularly in regions with high solar availability.

This project focuses on the design and development of a compact 20-liter solar water heater tailored for domestic use. The primary goal is to construct a system that maximizes heat absorption through optimized mechanical design, reflective enhancements, and the use of heat-trapping materials. A key feature of the system is the integration of a low-wattage water pump to facilitate effective water circulation, ensuring consistent and efficient heating.

The scope of the project includes designing a small-scale yet efficient heating unit, incorporating reflective and insulating components to improve thermal performance, and evaluating the system under real-world conditions to assess its effectiveness.

Through this project, we aim to demonstrate the viability of solar thermal technology for everyday household applications and highlight its potential for reducing dependence on conventional energy sources.

By providing a sustainable, eco-friendly alternative to electric water heaters, this system not only contributes to energy conservation but also promotes awareness about renewable energy solutions. The insights gained from this project may also serve as a foundation for future developments in small-scale solar heating systems.

II. Literature Review

The use of solar energy for domestic water heating has seen significant advancements, with researchers exploring various methods to enhance system efficiency and affordability. Comparative studies, such as by M.A. Sabiha et al [1], have shown that evacuated tube collectors perform better under low solar radiation, whereas flat-plate collectors are more effective in moderate climates, guiding appropriate collector selection based on regional conditions. To improve heat retention, A. Kumar et al [2] integrated phase change materials (PCM), which allowed for continued hot water supply during periods of low sunlight, highlighting PCM's thermal storage benefits.

Mathematical modeling plays a vital role in system design and performance evaluation. H.P. Garg et al [3] developed analytical tools considering parameters like solar insolation and ambient temperature to better understand efficiency behavior. Similarly, efforts to create hybrid systems have gained momentum; M. Esen et al [4] demonstrated a dual-purpose setup combining solar water heaters with thermoelectric generators, thereby producing both heat and electricity.

Long-term performance and real-world applicability have also been studied extensively. S.C. Mullick et al [5] evaluated seasonal variations in output through year-long data collection, identifying maintenance needs and performance trends. Complementary systems were explored by Tiwari and Sodha [6], who successfully enhanced distillation and heating by integrating solar stills with water heaters.

Design enhancements have further contributed to efficiency gains. S.S. Chand et al [7] demonstrated significant temperature increases using reflective sheets and black-coated absorbers, validating cost-effective improvements in compact units. A. Syed et al [8] took an affordability-first approach by constructing heaters with recycled steel pipes, proving their effectiveness in rural deployments.

Geometric design also plays a crucial role. A. Jaiswal et al [9] found that coiled pipe configurations improved heat exchange due to increased surface exposure. Meanwhile, material selection and automation strategies were reviewed by P.K. Nagarajan et al [10], who emphasized the importance of thermal storage and intelligent controls in next-generation systems.

Broader overviews by S.A. Kalogirou [11] and foundational works like that of Duffie and Beckman [12] have laid the theoretical and practical groundwork for solar thermal system development, covering efficiency metrics, design principles, and applications. These studies collectively form a strong foundation for small-scale, efficient, and affordable solar water heating systems, like the one developed in this project.

III. Material & Methodolodgy

The Mini 20 Liter Solar Water Heater project was designed and fabricated with a focus on durability, efficiency, compactness, and the ability to function reliably under rooftop environmental conditions. The methodology covers every stage from material selection to mechanical and electrical integration, emphasizing optimal solar energy utilization through practical construction techniques.

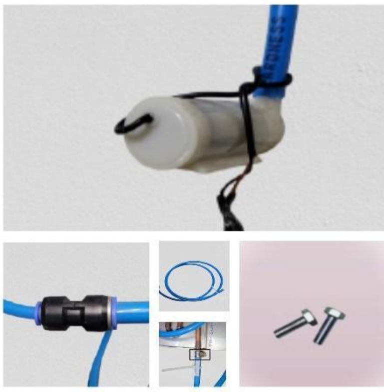
Materials Used :-

The materials chosen for this solar water heater were selected based on their mechanical strength, thermal conductivity, corrosion resistance, and cost-effectiveness. Each component contributes to the system's performance, structural integrity, and long-term reliability.

- **Steel/Copper Pipes:** Used as coiled tubes for the water path and primary solar heat absorption. The coiled design maximizes surface area exposure.
- **Metal Back Plate:** Acts as a heat absorber behind the coils. Though typically painted black for better absorption, a clear plate was used in this project for optimization.
- **Reflective Sheets (Aluminium):** Installed on both sides of the coil system to redirect and concentrate additional sunlight onto the pipes.

- **Water Tank (20 Liters):** Serves as the main reservoir for heated water. Compact, durable, and capable of maintaining heat for extended periods.
- **Frame Structure (Steel Rods):** Provides structural support and appropriate inclination for solar exposure (~45°).
- **Submersible Mini Pump (Aquarium type):** 12V DC, 50-watt pump for water circulation through the coils.
- **Blue Flexible Water Pipes:** Thermally resistant pipes for water transport between tank, coil, and pump.

- **Pipe Connectors & Hose Clamps:** For leak-proof joints and stable flow control.
- **Screws and Fittings:** Stainless steel fasteners for secure and rust-resistant assembly.



Fabrication Methodology :-

Fabrication of the system involved multiple precision-based processes to ensure functional integration and optimal thermal performance. The key steps included:

Machining Processes

- *Turning:* Used to shape cylindrical components, such as pipe ends and rods, for smooth and accurate connections.
- *Boring:* Employed to enlarge and finish pre-drilled holes, enhancing the fitting of structural supports.
- *Threading:* Enabled secure screw-fit connections between mechanical joints.
- *Drilling:* Used extensively for mounting holes, fasteners, and pipe connections.
- *Welding:* Provided high-strength permanent joints for structural frames and mounting brackets.

System Assembly :-

The complete assembly of the solar water heater was conducted in two main stages—mechanical and electrical—with detailed integration to ensure flow efficiency, solar alignment, and energy conservation.

Mechanical Assembly

- *Frame & Stand Construction:* Steel rods were cut, drilled, and welded into a triangular support stand, inclined at ~45° for maximum solar exposure.
- *Coil & Absorber Installation:* Steel pipes were coiled and fixed onto the flat metal plate using clamps and bolts. The metal plate acts as a solar collector, while side reflectors enhance the intensity.
- *Water Tank Mounting:* The tank was horizontally mounted on a fabricated platform, fitted with inlet/outlet ports, and securely fixed to prevent vibration or movement.
- *Plumbing:* Flexible pipes connected the tank to the pump and coiled pipes. Hose clamps ensured tight, leak-free joints. Bends were minimized to avoid flow restrictions.

Electrical Assembly

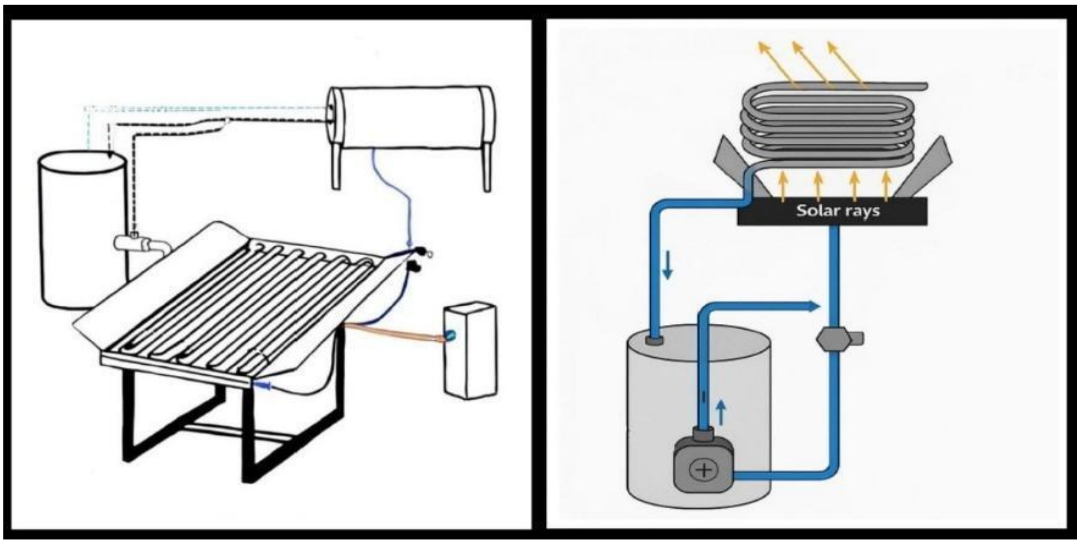
- *Pump Placement:* A submersible mini pump was inserted inside the water tank and connected to the coil's inlet.
- *Wiring & Power Supply:* A 12V DC power supply was used to power the pump. All wires were secured with cable ties, and connections were waterproofed for safety.
- *Flow Testing:* The system was tested to ensure proper circulation, absence of leaks, and flow stability.

Working Principle & Procedure :-

The heater operates on the principle of solar thermal energy absorption and forced water circulation. The detailed working mechanism is as follows:

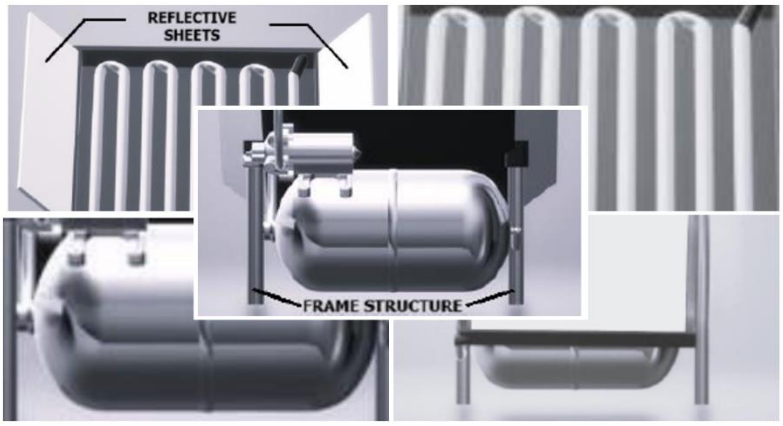
- **Tank Filling:** Clean water is filled in the 20-liter storage tank before system operation.
- **Pump Activation:** The pump circulates water through the steel coils exposed to sunlight.
- **Heat Absorption:** Sunlight heats the black-painted steel coils; the metal back plate and side reflectors boost absorption.
- **Thermal Circulation:** Water circulates in a closed loop—repeatedly passing through the heated coil—resulting in gradual temperature rise.

- **Storage:** The warmed water returns to the tank, where heat accumulates over time.
- **Hot Water Access:** Heated water is available through a separate outlet for use.
- **Energy Efficiency:** The system uses only ~50W of power for the pump, with the rest of the energy provided freely by the sun.
- **Safety & Durability:** All components are chosen for outdoor suitability, and secure fittings ensure minimal maintenance.

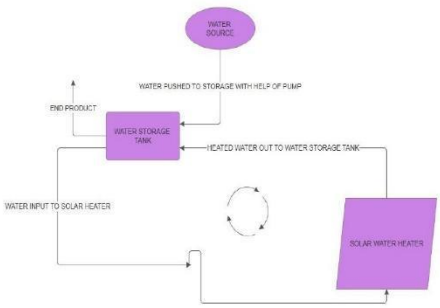


Final Alignment & Performance Checks :-

- Frame was stabilized and reflectors were adjusted for optimal solar focus.
- The system was filled and operated to check water flow, pump function, and solar heating efficiency.
- Leak points were identified and resolved before full-scale testing.
- Efficiency was monitored over different daylight hours to validate heating capability.



IV. Schematic Diagram & Real time assembly picture of project

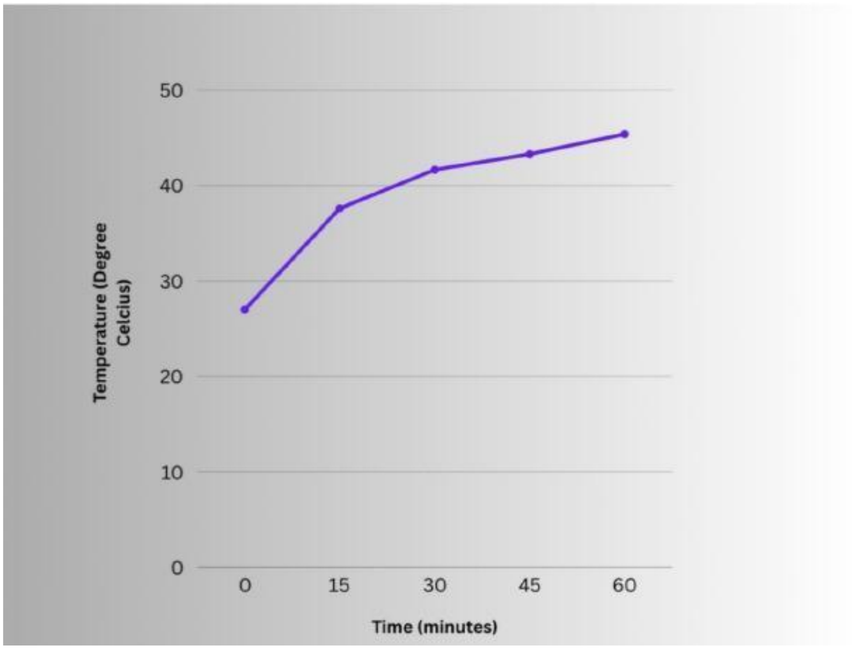


V. Observations, Graphs & Calculations

To evaluate the performance of the Mini 20 Liter Solar Water Heater, the temperature of the water was recorded at regular intervals over a period of 15 minutes under direct sunlight. The initial water temperature was taken at ambient conditions, and the pump was activated to begin circulation through the coiled steel pipes.

The water temperature increased steadily over the hour as it passed through the heated steel coils. The backplate and reflective sheets played a key role in concentrating solar radiation and enhancing thermal absorption. The temperature was recorded in Fahrenheit and then converted to Celsius.
Below is the tabulated data recorded during the test:

Time (minutes)	Temperature (°C)
0	27
15	37.6
30	41.6
45	43.7
60	45.6



A positive slope confirms the consistent heat absorption and transfer capability of the system. The curve shows a rapid increase in the first 30 minutes, followed by a gradual rise, indicating effective thermal saturation and retention.

REAL TIME PROJECT CALCULATIONS BASED ON OBSERVATIONS

INLET TEMPERATURE (T_i)

This is the temperature of the water when it enters the solar collector system.

Ti = 27°C (Based on initial observation)

OUTLET TEMPERATURE (T_o)

This is the temperature of the water after it has circulated through the collector and returned to the tank.

To = 46°C (Based on 60-minute observation result)

MEAN TEMPERATURE DIFFERENCE (ΔT_m)

Mean temperature difference helps evaluate the average temperature gain across the system.

$$\Delta T_m = \frac{T_o + T_i}{2} = \frac{46 + 27}{2} = 36.5^\circ C$$

OTHER POSSIBLE CALCULATIONS BASED ON ASSUMPTIONS

TOTAL HEAT GAINED (Q)

We use the formula:

$$Q = m \cdot c_p \cdot \Delta T$$

Where:

- **m** = mass of water (kg) = 20 liters = 20 kg (assuming 1 liter of water ≈ 1 kg)
- c_p = specific heat of water = 4186 J/kg·°C
- **ΔT** = To - Ti = 46 - 27 = 19°C

$$Q = 20 \cdot 4186 \cdot 19 = 1,590,680 \text{ Joules} = 1.59 \text{ MJ}$$

SOLAR ENERGY ABSORBED (Q_s)

Assuming average solar radiation intensity (G) = 600 W/m²

Assuming absorber area (A) = 0.75 m²

Duration (t) = 1 hour = 3600 seconds

$$Q_s = G \cdot A \cdot t = 600 \cdot 0.75 \cdot 3600 = 1,620,000 \text{ Joules} = 1.62 \text{ MJ}$$

SYSTEM EFFICIENCY (η)

$$\eta = \frac{Q}{Q_s} = \frac{1,590,680}{1,620,000} = 0.981 = 98.1\%$$

VI. Result & Discussions

The construction and testing of the Mini 20 Liter Solar Water Heater were successfully completed as per the specified design and engineering requirements. The final assembled system included tightly coiled steel pipes mounted on a flat metal backplate, accompanied by dual side reflectors to enhance solar radiation absorption. A low-power submersible pump was integrated into the water tank to ensure continuous circulation of water through the heating coils.

During testing under clear and direct sunlight conditions, the system demonstrated effective performance by increasing the water temperature from an initial 27°C to 46°C within approximately one hour. This result reflects a notable thermal efficiency and confirms the viability of the system in delivering hot water using only solar energy, without relying on electric heating elements.

The efficient heat absorption was achieved through the combination of multiple design elements: the black-painted coils for optimal solar gain, the reflective sheets to redirect additional sunlight toward the pipes, and the metal backplate that helped retain and radiate heat back into the coils. These collectively improved the system's thermal collection capacity, resulting in quicker water heating.

From a practical standpoint, the compact and modular nature of the heater allows it to be easily installed on rooftops or other open surfaces without major structural modifications. The use of a 50W submersible pump makes the system highly energy-efficient, consuming minimal power while maintaining a steady water flow rate. This translates into a more than 99% energy savings compared to conventional electric water heaters.

Moreover, the use of readily available and cost-effective materials makes this design both affordable and replicable. Its low maintenance requirements and mechanical simplicity make it suitable for a wide range of users, especially in off-grid, rural, or energy-conscious urban settings.

However, the performance is inherently dependent on solar intensity and weather conditions

VII. Conclusion & Future research scope

This project was initiated in response to the increasing demand for sustainable and energy-efficient water heating solutions, especially in regions with high solar insolation. The aim was to design, develop, and experimentally validate a compact, low-cost solar thermal system capable of heating 20 liters of water with minimal electrical input.

The major contributions of this study include the selection of an effective solar thermal model based on cost and efficiency, the fabrication of coiled steel pipe collectors optimized for thermal performance, and the integration of reflective concentrators and a black-painted metal absorber plate. A custom-designed frame held the entire assembly at a 45-degree tilt to maximize year-round solar exposure.

Real-world rooftop testing of the fully constructed 3D prototype demonstrated its practical efficiency. Water temperature increased from 27°C to 46°C within 60 minutes of direct sunlight, validating the thermal collection design. A low-power submersible pump, pipe connectors, and a custom-insulated storage tank were combined to form a functional closed-loop heating system. Observational data and performance metrics confirmed that the prototype offers a renewable and cost-effective alternative to traditional electric water heaters.

The successful fabrication and testing of this system underscore its potential for domestic and small-scale commercial applications. The simplicity of the design and its low maintenance requirements make it especially suitable for off-grid areas and energy-conscious households. Nonetheless, opportunities for further enhancement remain.

Future Research Directions :-

The system's current performance can be significantly improved with advanced technologies and design integrations. Key future research directions include:

- *Smart Automation:* Incorporating IoT-based control systems to automate pump operation based on real-time temperature and solar intensity data. This would optimize performance while minimizing manual oversight.
- *Advanced Materials:* Research into selective coatings for absorber plates and the use of vacuum-insulated storage tanks could enhance heat absorption and retention.
- *Thermal Energy Storage:* The addition of phase change materials (PCMs) or compact thermal batteries would enable hot water availability during low-sunlight or nighttime conditions.
- *Modular and Scalable Design:* Developing a scalable architecture would allow customization based on user needs, enabling applications ranging from individual homes to community-level systems.
- *Hybrid Systems:* Integrating the system with photovoltaic panels could allow simultaneous electricity and hot water generation, paving the way for self-sufficient energy units.
- *User Interface Enhancements:* Mobile apps and smart displays for monitoring system performance, temperature, and usage patterns could improve user experience and system management.

Possible Modifications for Future Prototypes

Several enhancements were identified during the project but could not be implemented due to time and budget constraints. These include:

- *Sedimentation-Based Water Filter*: Integrating a simple natural sedimentation filter at the inlet to purify incoming water and protect system components.
- *Sun-Tracking Mechanism:* Using light sensors and a rotatory joint to adjust the system's orientation throughout the day, ensuring maximum solar exposure at all times.

- *Photovoltaic-Thermal Hybrid Panel:* Replacing the metal backplate with a PVT panel to enable simultaneous water heating and electricity generation, powering the pump and potentially reducing external energy needs.
- *LCD Temperature Display:* Adding a digital display to show real-time water temperature for user convenience and better performance monitoring.

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