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Theoretical Design and Analysis of a Solar Water Heating System

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Abstract

This study presents the theoretical design and performance analysis of a Solar Water Heating System (SWHS) tailored for the climatic conditions of Buraimi, Oman. Using site-specific meteorological data, including solar radiation and ambient temperatures, a closed-loop SWHS was designed. The system features a Blue Tinox-coated absorber plate, a 425 liters insulated storage tank, and a flat plate solar collector optimized for high thermal efficiency. Seasonal energy requirements were calculated using average ambient temperatures. The system demonstrates significant potential for reducing energy consumption, with an estimated payback period of 10 years and annual savings of 100.81 OMR. This work supports sustainable energy initiatives in Oman by showcasing the feasibility of implementing solar thermal systems in arid climates.

Keywords: Solar Water Heating System, SWHS, Thermal Efficiency, Oman, Renewable Energy, Flat Plate Collector, Solar Radiation, Energy Savings

1. Introduction

1.1. Solar Energy and Its Importance

Solar energy, an abundant and sustainable form of renewable energy, has become a pivotal solution in addressing the global energy demand and the environmental impact of fossil fuel consumption. Among the diverse applications of solar energy, solar thermal technologies particularly solar water heating systems (SWHS) have garnered significant attention due to their efficiency in harnessing solar radiation for domestic and industrial heating purposes [1]. A SWHS captures solar thermal energy through collectors and transfers it to a working fluid, typically water, which is then stored in an insulated tank for later use. This technology offers an eco-friendly and economically viable alternative to conventional electric and gas water heaters. The use of solar thermal systems substantially reduces greenhouse gas emissions and dependency on non-renewable sources [2]. Given the increasing global interest in sustainable energy solutions, SWHS represents a critical component of the transition to clean energy, especially in regions with high solar irradiance such as Oman. This study focuses on the theoretical design and performance analysis of a solar water heating system specifically

tailored for the climatic conditions of Buraimi, Oman. It emphasizes the need to develop efficient, region-specific SWHS models that utilize local solar resources and support national sustainability goals.

1.2. Overview of Solar Water Heating Systems (SWHS)

SWHS are categorized into active and passive systems based on the mode of fluid circulation. Active systems use pumps and controllers to circulate the heat transfer fluid, providing better efficiency and control, while passive systems rely on natural convection [3]. The most commonly used collector types include flat plate collectors (FPCs) and evacuated tube collectors (ETCs). FPCs are widely favored due to their simple design, cost-effectiveness, and ease of maintenance [4]. A typical SWHS consists of several essential components: (a) Solar Collector: Captures and converts solar radiation into thermal energy, (b) Storage Tank: Stores heated water for later use, (c) Insulation Material: Minimizes heat loss and improves system efficiency, (d) Piping System: Transfers the heat between the collector and the storage tank, and (e) Heat Exchanger: Allows thermal transfer in closed-loop systems without direct fluid mixing. The system design, performance, and efficiency depend heavily on the choice of materials, solar collector configuration, orientation, and thermal properties of the components [5].

1.3. Environmental and Economic Benefits

The deployment of SWHS offers notable environmental benefits by reducing carbon dioxide emissions. Studies have shown that replacing electric or gas water heaters with solar-based systems can reduce household emissions by up to 3,000 kg annually [6]. In addition to environmental sustainability, SWHS offers long-term economic benefits. Although the initial capital cost may be higher, the payback period is typically short (ranging from 4 to 8 years), and the system continues to deliver energy savings for over a decade. Furthermore, government incentives, including tax rebates and subsidies, further enhance their economic viability [7].

1.4. Applications and Regional Relevance

SWHS technology has been widely implemented in countries such as Germany, China, and Australia through national-level incentives and regulations. These regions have demonstrated that SWHS can be successfully integrated into both residential and commercial infrastructures [8]. Oman, with its high solar insolation, presents an ideal location for implementing SWHS on a broader scale. Particularly in Buraimi, the climatic conditions—characterized by high solar radiation and clear skies support the efficient operation of solar thermal systems [9]. However, local environmental challenges, such as dust accumulation and temperature fluctuations, necessitate the development of customized designs. This study aims to address these issues by optimizing the design parameters of SWHS suitable for arid climates.

1.5. Challenges and Future Prospects

Despite their advantages, SWHS face challenges including location dependency, maintenance complexity, and performance degradation due to scaling and corrosion. However, ongoing innovations in materials, smart control systems, and insulation technologies are continually improving system efficiency and durability [10]. In Oman, optimizing the system based on local solar irradiance, ambient temperature, and user demand patterns is essential to ensure year-round efficiency and reliability [11].

1.6. Study Objectives

This research is aimed at developing a theoretical framework for the design and optimization of a solar water heating system suited to Buraimi's climate. The main objectives of the study are:

- To evaluate solar radiation parameters specifically Direct Normal Irradiance (DNI), Global Horizontal Irradiance (GHI), and Diffuse Horizontal Irradiance (DHI), using location-specific meteorological data.
- To design the key components of a SWHS (collector, tank, heat exchanger) for optimal performance.
- To assess seasonal performance variation of the SWHS based on ambient conditions.
- To conduct an economic analysis to determine the payback period, cost savings, and system feasibility.

2. Methodology

2.1. System Description

This study focuses on the design and theoretical evaluation of a closed-loop Solar Water Heating System (SWHS) tailored for Buraimi, Oman [12]. The system comprises a flat plate solar collector, a 425-liter insulated stainless steel storage tank, a copper coil heat exchanger, and associated piping and control mechanisms. The system schematic is presented in Fig. 1, and the components are listed in Table 1. The closed-loop configuration uses a heat exchanger to transfer thermal energy from the solar collector to the storage tank without direct contact between the heating fluid and usable water, enhancing system safety and longevity.

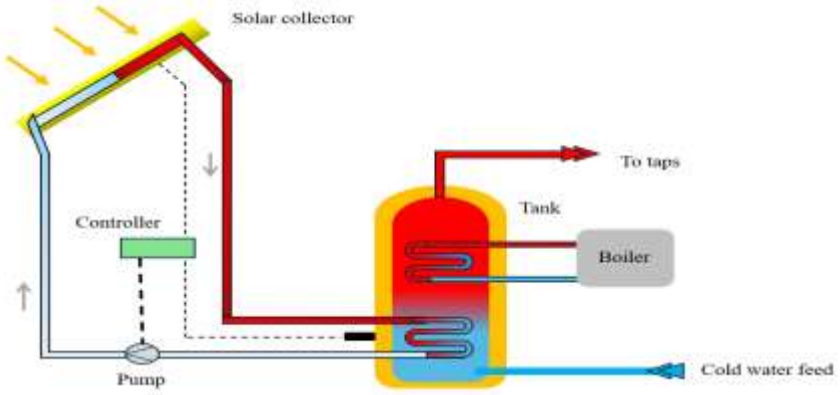


Fig. 1: Schematic of a Solar Water Heating System (SWHS).

Table 1: Main Components of a Solar Water Heating System and their Functions

S. No.:	Main Components	Description
1	Solar Collector	Captures solar energy and transfers it to the water.
2	Storage Tank	Insulated reservoir that stores the heated water.
3	Heat Exchanger	Facilitates heat transfer from the collector to the water without mixing fluids.
4	Circulation Pump (for active systems)	Moves water or heat-transfer fluid through the system.
5	Controller (for active systems)	Manages the operation, ensuring optimal performance.
6	Piping System	Transfers heated water between the collector, tank, and user outlets.
7	Expansion Tank (optional)	Accommodates the expansion of heated fluid in a closed-loop system, preventing pressure build-up.
8	Temperature Sensors	Monitors the temperature of the fluid, enabling the controller to optimize system operation.

2.2. Solar Radiation and Environmental Parameters

Solar irradiance data specific to the University of Buraimi (latitude 24.2354°N, longitude 55.8914°E) was collected from the NASA POWER platform and validated against the Global Solar Atlas database. The analysis focused on DNI, GHI, DHI, and GTI. The average daily total solar irradiation was estimated to be 5.15 kWh/m²/day, and annual irradiation values reached 1879.9 kWh/m²/year. These values support the viability of solar-based thermal systems in Buraimi. Fig. 2(a–b), Fig. 3(a–b), and Fig. 4(a–b) show comparisons of solar components and yearly trends.

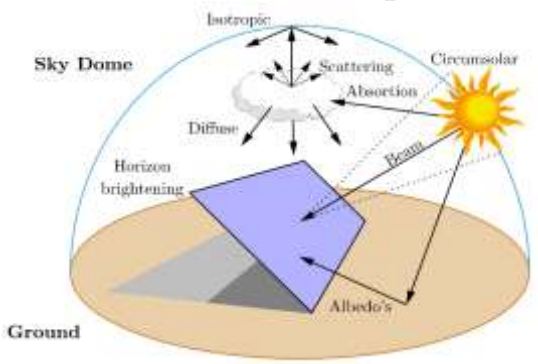


Fig. 2(a) Diagram illustrating the components of solar radiation direct, diffuse, and reflected.

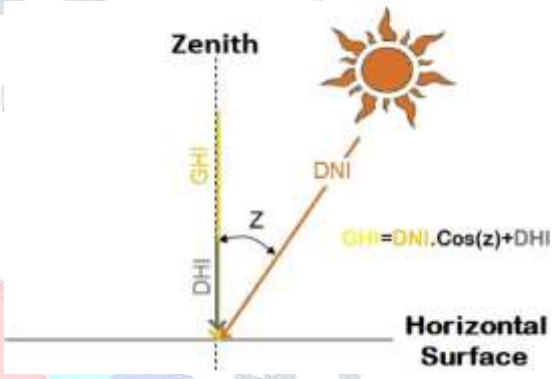


Fig. 2(b) Global, direct and diffused radiation on a horizontal surface.

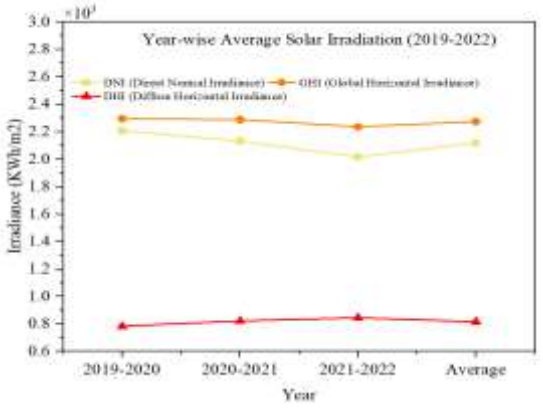


Fig. 3(a): Year-wise Average Solar Irradiation (NASA Power)

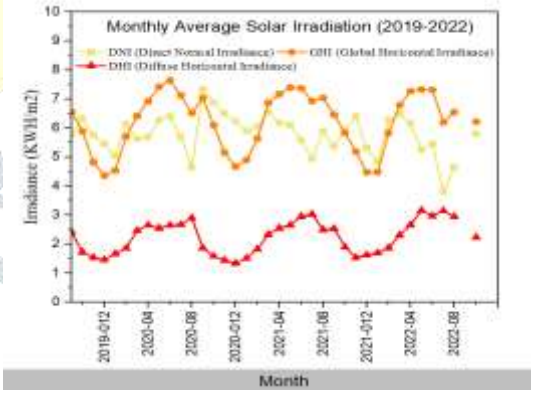


Fig. 3(b): Monthly Average Solar Irradiation (NASA Power)



Fig. 4(a): Daily Solar Irradiation Data (Global Solar Atlas)

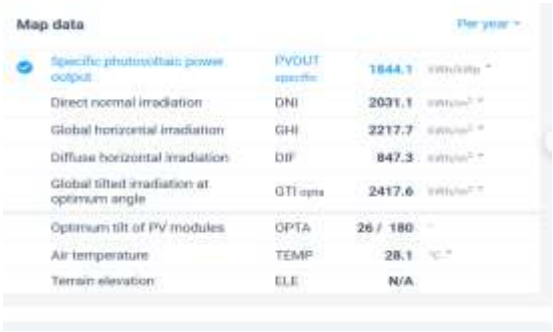


Fig. 4(b): Annual Solar Irradiation Data (Global Solar Atlas)

2.3. Load Estimation and Storage Tank Sizing

A 425-liter storage tank was selected based on average household usage for 7 individuals, as shown in Table 2 and Fig. 5. Daily hot water usage varied from 315 to 525 liters, with Friday typically being the peak day. The tank is fabricated

from stainless steel, offering corrosion resistance and long service life. It is insulated with polyurethane foam of 50 mm thickness, which exceeds the calculated critical insulation radius of 8.7 mm, thereby ensuring effective thermal resistance as shown in Fig. 6(a-b).

Table 2: Weekly water consumption

Day	For 1 Person Consumption (liters)	For 7 Person Consumption (liters)
Sunday	60	420
Monday	55	385
Tuesday	50	350
Wednesday	45	315
Thursday	60	420
Friday	75	525
Saturday	70	490
in one week	415	2905
Average / Day	59.2	415
Assume Selection		425

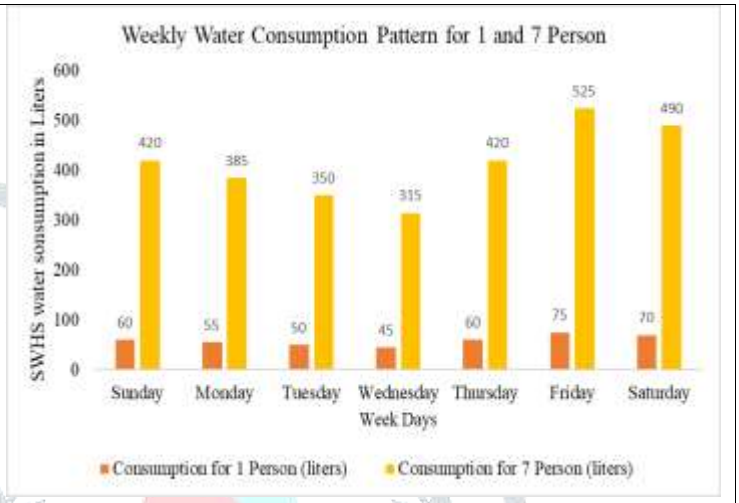


Fig. 5: Weekly water consumption pattern

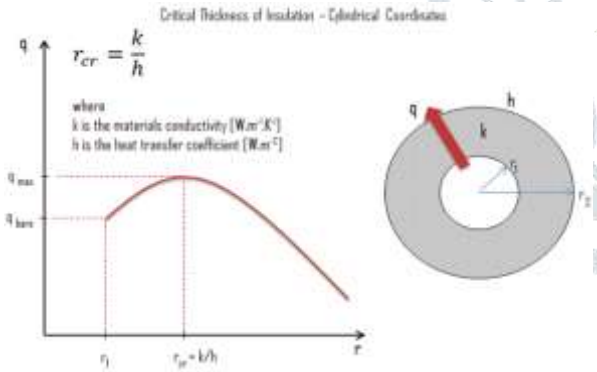


Fig. 6(a) Critical Thickness of Insulation in Cylindrical Coordinates

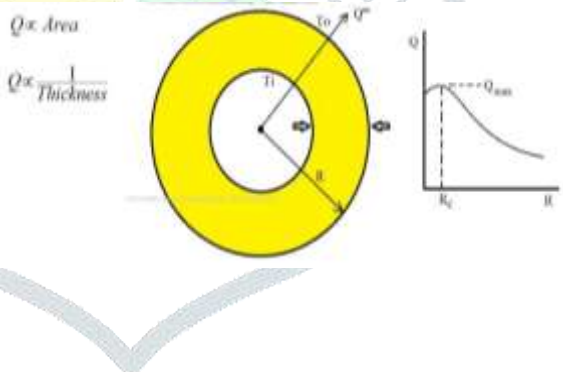


Fig. 6(b) Heat Transfer through Insulated Pipe

2.4. Collector Design and Configuration

The flat plate solar collector was designed with dimensions of 1.009 m × 2.009 m and features: An absorber plate coated with Blue Tinox for high absorptivity (0.95) and low emissivity (0.13), Low-iron tempered glazing for transparency (τ = 0.915), Copper pipes for heat transfer (10 risers, 6.15 mm diameter), 40 mm rock wool insulation for thermal protection. Design schematics are illustrated in Fig. 7(a-b). Material properties are summarized in Table 3.

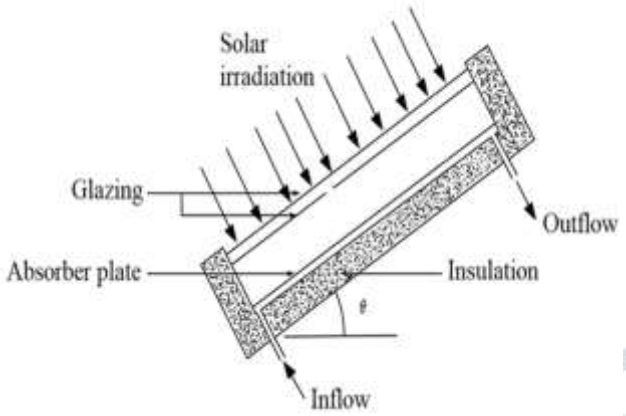


Fig. 7(a) **schematic cross-sectional diagram** of a flat-plate solar collector.

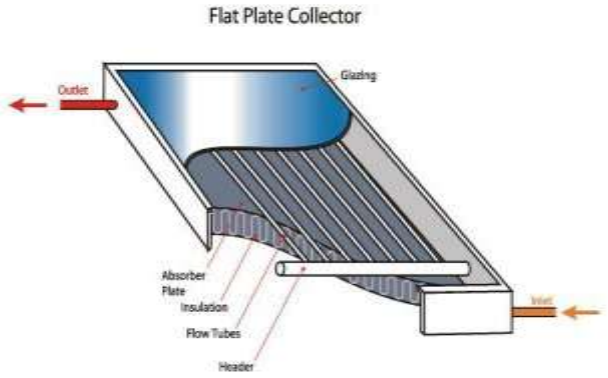


Fig. 7(b) **3D diagram** of a flat-plate solar collector.

Table 3 Detailed Specifications of the Solar Water Heating System Component

Components	Values
Width	1009 mm
Height	2009 mm
Depth	75 mm
Width Module Size	1040 mm
Full Solar Surface	2.03 m^2
Free Glass Surface	1.78 m^2
Absorber Surface	1.78 m^2
Liquid Space Capacity	1.571 L
Cover Glass Thickness	4 mm
Thermal Insulation Thickness/Material	40 mm rock wool
Absorber Absorption Coefficient	0.95
Absorber Emission Factor	0.13
Material of Absorber Plate	Copper
Thermal Conductivity of Plate Material	386 W/m·K.
Density of Plate Material	8954 kg/m³.
Plate Thickness	0.15 inches (38.1 mm)
Collector Angle	30 degrees
Location of Collector Tray	Bottom
Diameter of the Tube	6.15 mm
Tube Center-to-Center Distance	100 mm (approximately)
Number of Tubes Used	10
Diameter of Header Pipes	0.7 inches (12.7 mm)

2.5. Thermal Energy Requirement

Thermal energy required to heat the 425 liters of water from average ambient temperatures to 60°C was calculated using:

$$Q = m \times C_p \times \Delta T$$

where m = 0.425 m^3, Cp=1.16 kWh/m3°C, and ΔT varies monthly as given in Table 4. Monthly energy requirements ranged from 10.94 to 20.36 kWh/day, showing higher demand in winter months. This variation is presented in Fig. 8.

Table 4: Monthly Temperature Difference ΔT and Energy Requirement for Heating Water to 60°C.

Month	ΔT (oC)	Energy (KWh)
January	= (60 – 18.7) = 41.3	20.3609
February	= (60 – 20.3) = 39.7	19.5721
March	= (60 – 24.1) = 35.9	17.6987

April	= (60 – 29.9) = 30.1	14.8393
May	= (60 – 33.5) = 26.5	13.0645
June	= (60 – 37.6) = 22.4	11.0432
July	= (60 – 37.8) = 22.2	10.9446
August	= (60 – 38) = 22	10.846
September	= (60 – 35.4) = 24.6	12.1278
October	= (60 – 30.4) = 29.6	14.5928
November	= (60 – 25.3) = 34.7	17.1071
December	= (60 – 21) = 39	19.227

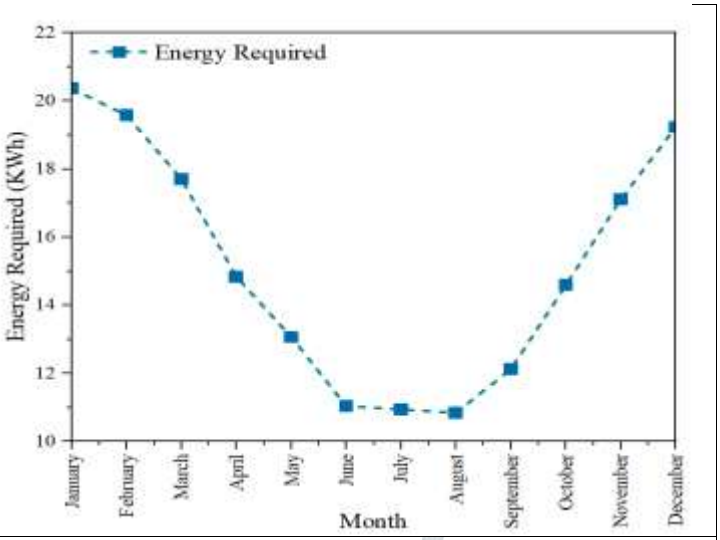


Fig. 8 Monthly Energy Requirement for Heating Water to 60°C.

2.6. Heat Gain and System Efficiency

The absorbed solar energy was estimated using:

$$q_s = \tau_g \alpha G_t = 0.915 \times 0.95 \times 5146 = 4473\ Wh/m^2$$

Total heat loss:

$$q_{loss} = U_t(T_{mean} - T_{ref}) = 6.105 \times (70 - 25) = 274.7\ Wh/m^2$$

Thus, useful heat gain:

$$q_{useful} = 4473 - 275 = 4198\ Wh/m^2$$

Required collector area for 15.12 KWh/day:

$$A = \frac{15.12 \times 1000}{3778.2} = 4.001\ m^2$$

Efficiency was calculated using:

$$\eta = F_R \left[\tau_\alpha - \frac{U_t(T_f - T_a)}{G_t}\right]$$

$$\eta = 0.937 \left[(0.915 \times 0.95) - \frac{6.105(70-29.33)}{5146}\right] = 76.9\%$$

2.7. Heat Exchanger Design

A copper coil heat exchanger was designed for indirect heating. It comprises 5 spiral coils with a radius of 10 cm, spaced at 4 cm, totaling 30 cm in height. Copper was selected due to its high thermal conductivity (385 W/m·K), ensuring efficient heat transfer.

2.8. Flow Dynamics and Reynolds Number

Flow dynamics were assessed by calculating the **Reynolds number**:

$$Re = \frac{\rho v D}{\mu}$$

With flow rate of 5 L/min and pipe diameter of 38.1 mm, the calculated Reynolds number was 2737.81, indicating turbulent flow.

3. Results and Discussion

3.1. Thermal Performance of the Solar Collector

The theoretical thermal performance of the designed flat-plate solar collector indicates a useful heat gain of 4198 Wh/m² with a final collector heat flux of 3778.2 W/m². With an average heating requirement of 15.12 kWh/day for 425 liters of water, the system requires a total collector area of 4.001 m², which was practically realized using two plates of 2 m² each. The thermal efficiency of the collector, determined using the Hottel–Whillier–Bliss equation, was calculated as:

$$\eta = F_R \left[\tau_\alpha - \frac{U_t(T_f - T_a)}{G_t}\right] = 76.9\%$$

This high efficiency is attributed to the use of Blue Tinox-coated absorber plates, optimized insulation, and favorable solar irradiance in Buraimi.

3.2. Economic Feasibility and Annual Savings

The system's economic viability was assessed by comparing the energy consumption and cost savings against conventional electric water heating. The daily energy requirement (Q_{load}) was calculated as:

$Q_{load} = m \,.\, C_p \,.\, (T_{hot} - T_{cold}) = 425 \times 4.18 \times (60 - 20) = 71060\ KJ/day \approx 19.74\ KWh/day$

Using an electricity rate of 0.014 OMR/KWh, the annual savings achieved through the SWHS are:

Annual Savings $= 365 \times 0.014 \times 19.74 = 100.87\ OMR/year$

3.3. Approximate Estimation of Initial Cost of Solar Water Heater [through various sources]:

This section provides an approximate estimation of the initial cost involved in constructing a solar water heater. Each major component required for the assembly has been carefully listed along with its estimated cost in Omani Riyal (OMR). A detailed breakdown of costs, including the tank, insulating material, collector, piping, and various other essential materials, is outlined. To better visualize the distribution of costs across these components, Fig. 9 illustrates the percentage contribution of each component to the total initial cost.

1. Tank:
   - Capacity: 425 liters.
   - Material: Stainless steel.
   - Estimated cost: 140.00 OMR (adjusted for increased capacity).
2. Polyurethane Insulating Material:
   - High-performance polyurethane for tank insulation.
   - Estimated cost: 95.00 OMR (adjusted for tank size and insulation thickness).
3. Flat Plate Collector:
   - Material: Blue Tinox with selective coating for high solar absorption efficiency.
   - Estimated cost: 105.00 OMR.
4. Holder for the Plate Collector:
   - Material: Aluminum or other durable material.
   - Used to maintain optimal tilt angle for solar radiation.
   - Estimated cost: 40.00 OMR.
5. Copper Riser Pipes:
   - Quantity: 10 risers, each 1.9 meters in length.
   - Total length: 19 meters.
   - Estimated cost: 38.00 OMR.
6. Additional Piping:
   - 0.25-inch pipes (30 feet): For smaller connections.
     - Estimated cost: 50.00 OMR.

- 1-inch pipes (10 meters): For main inlet and outlet lines.
  - Estimated cost: 45.00 OMR.

7. Glass Cover:
   - Type: Low iron tempered glass with a thickness of 3.2 mm.
   - Emissivity: 0.19.
   - Estimated cost: 45.00 OMR.
8. Frame:
   - Material: Aluminum.
   - Thickness: 0.5 mm.
   - Estimated cost: 15 OMR.
9. Low Tempered Iron Glass:
   - Estimated cost: 25 OMR.

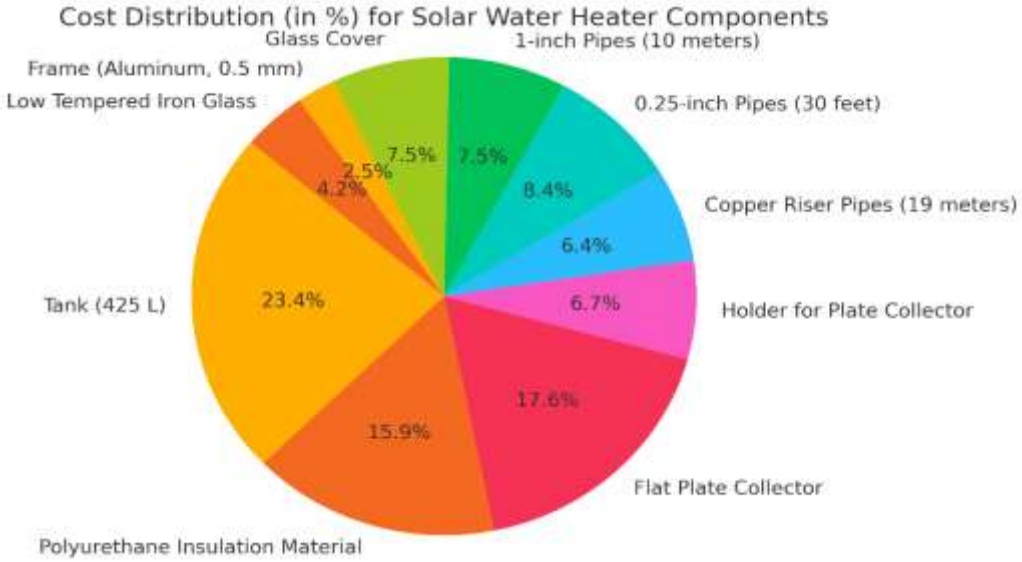


Fig. 9 Cost Distribution (%) for Solar Water Heater Components.

3.4. Payback Period Analysis:

The payback period helps determine the time required to recover the initial investment. The formula used is:

$$\text{Payback Period (in years)} = \frac{Total\ Cost}{Annual\ Saving}$$

Given Data:

- Total Cost: 598 OMR (from the cost estimation of the solar water heater).
- Annual Saving: 100.87 OMR/year

Payback Period Calculation:

$$Payback\ period\ Period = \frac{598}{100.87} \approx 5\ years\ and\ 11\ months$$

3.5. Payback Period and Long-Term Benefits:

The solar water heater is a cost-effective and sustainable solution for small villas and households in Oman. For a family of seven, the system ensures hot water availability without additional energy costs for approximately 10 years. With a lifespan of 15–20 years for the tank and collector, the system offers long-term savings and supports sustainable energy usage.

4. Conclusions

This study presents a comprehensive theoretical design and performance analysis of a closed-loop Solar Water Heating System (SWHS) tailored to the climatic conditions of Buraimi, Oman. The system was developed using detailed site-specific solar irradiance data, optimized component design, and thermal modeling. Key elements such as a Blue Tinox-coated absorber plate, a 425-liter stainless steel insulated storage tank, and a high-efficiency flat plate collector were carefully selected and dimensioned to maximize energy capture and minimize losses. Thermal performance evaluation indicated a high collector efficiency of 76.9%, with a useful heat gain of 4198 Wh/m² and a final heat flux of 3778.2 W/m². The system effectively meets the daily hot water demand for a seven-member household, demonstrating strong seasonal adaptability. The economic analysis revealed an estimated payback period of approximately six years, with annual energy savings of 100.87 OMR, validating the long-term financial viability of the system. The findings confirm that implementing SWHS in arid regions like Buraimi is both technically feasible and economically sustainable. Beyond cost savings, the system significantly contributes to environmental sustainability by reducing dependence on fossil-fuel-based water heating and lowering carbon emissions. This research supports national and global initiatives promoting renewable energy adoption and provides a practical design framework for localized SWHS development. Future work may include prototype fabrication, experimental validation, and real-time performance.

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